Chapter 7
High School
Three-Course Model

2016 Science Framework

FOR CALIFORNIA PUBLIC SCHOOLS
Kindergarten Through Grade Twelve

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To view the remaining sections of the 2016 California Science Framework on the CDE website, go to:
https://www.cde.ca.gov/ci/sc/cf/cascienceframework2016.asp

Items in this document that relate to crosscutting concepts are highlighted in green and followed by the abbreviation CCC in brackets, **[CCC]**, with a number corresponding to the concept. The same items that correspond to the science and engineering practices are highlighted in blue and followed by the abbreviation SEP in brackets, **[SEP]**, with a number corresponding to the practice.

The Web links in this document have been replaced with links that redirect the reader to a California Department of Education (CDE) Web page containing the actual Web addresses and short descriptions. Here the reader can access the Web page referenced in the text. This approach allows CDE to ensure the links remain current.

High School Three-Course Model

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 California Next Generation Science Standards (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 into courses. This chapter describes ways in which the performance expectations for high school could be bundled together into instructional segments 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 of this framework outlines an integrated three-year high school model called Every Science, Every Year.

High School Three-Course Model Introduction

The three-course model combines all high school performance expectations 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 presents an integration of ESS and one of the other high school domains. In each course, the integration adds value to both domains 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 domains while understanding of each domain 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 and Space Science

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

Organization Within Courses

The performance expectations 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 performance expectations 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 performance expectations provides the breadth and depth required to address the key content ideas that students need. Performance expectations within each course in this framework 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 performance expectations. Furthermore, the clarification statements and assessment boundaries associated with the performance expectations in the bundle are 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 framework 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 framework provides examples and suggestions; it does not dictate requirements. The selections of performance expectations in each instructional segment bundle presented in this chapter are only one example of the way performance expectations could be coherently organized. There are a variety of possible alternative paths and different interplays among overarching themes identified in each instructional segment 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 needs of the specific students who 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 performance expectations 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 California 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 performance expectations in the CA NGSS is smaller than the number of standards in the 1998 Science Standards, performance expectations require a deeper understanding. It is critical that teachers look at the verbs embedded in each performance expectation 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 to apply science and engineering practices to uncover and elucidate crosscutting concepts that have applications across many disciplinary core ideas. In addition to this 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 performance expectations.

All Standards, All Students

The CA NGSS high school performance expectations are the assessable statements of what *all* students should know and be able to do by the end of grade twelve. In other words, the performance expectations represent the minimal assessable standards for which all high school students should be held accountable. Each of the performance expectations has assessment boundaries to guide those who construct standardized assessments. Thus, the performance expectations 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 CA NGSS appendixes.

Course-Sequencing Discussion

California’s high schools operate largely under local control. As such, course offerings and the order in which courses are offered for high school science are local education agency (LEA) decisions. As a result, this framework prescribes neither the courses to be offered nor the order in which they are offered. Instead, LEAs may consider multiple course sequences. The proposed Every Science, Every Year integrated model (appendix 4 of this framework) has a set sequence but the four-course discipline specific and three-course integrated Earth and space science models do not.

As decision makers, LEAs have several factors to consider when deciding what will best meet their students' needs. They should try not to let tradition and staffing be the only factors they consider as they 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, and then physics—has been in place for more than 100 years since the Committee of Ten first met. In our twenty-first century world, this may not make the most sense. As LEAs decide among the twenty-four permutations for course sequence in the four-course model and six possibilities for the three-course model, they need to be thoughtful about their 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 LEAs with the decision:

- Is the 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. This may recruit more students into STEM and science classes (and possibly STEM-related careers and college majors).
- What course(s) are viewed as most important to the community? Put those classes first because some percentage of students will take the minimum requirements for graduation.
- How many science classes are students in the LEA required to take in order to graduate? How many science classes do students in the LEA typically take? What science concepts and ideas does the LEA want to be sure that all students have if they do not take the full scope of the CA NGSS? These questions all have implications for choosing which classes (and ideas) come earliest.
- What science ideas does the LEA think juniors and seniors are more developmentally ready to learn than freshmen and sophomores?
- What concepts and ideas does the LEA think are more concrete so should be placed earlier in the sequence, with more abstract ideas coming later in the learning process?

- As the LEA considers individual discipline focused classes, they should look at the performance expectations. Should some performance expectations from other domains be mastered for students to be successful in a particular course? If so, that has implications for sequencing.

The decision LEAs are being asked to make is not trivial. Therefore, LEAs should spend time on the decision and consult with their science teachers. Ultimately, the LEA needs to determine a two-, three-, or four-year sequence of course offerings. Whichever course sequence is selected, the LEA 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 to demonstrate that courses are interconnected and that 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 the LEA determines in what order to place courses.

Living Earth Early or Late in the Sequence?

There are several good arguments for placing biology early in the sequence: (1) biology has a better track record of interesting girls in science (AAUW 2010; Baram-Tsabari and Yarden 2011); (2) some teachers are more comfortable with its earlier placement in the sequence; and (3) students 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, and much of biology today explores and explains things at the molecular or cellular level. Therefore, the LEA should consider the following question: How could topics in high school biology 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. Therefore, 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 more abstract than biology, dealing with phenomena unseen to the naked eye and frequently not intuitive to students. Knowing the students and community will help the LEA decide if students 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. Many argue having physics later in the course sequence allows concepts to be introduced through a more mathematically rigorous lens. Others argue having physics earlier in the sequence is approachable to students as the concepts are concrete and relate to students' everyday lives. 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 https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link1.) 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 learning, 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 https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link2 for questions about authorization to teach integrated courses.

The Living Earth: Integrating Biology and Earth Science

The interactions between the biosphere and the rest of Earth's systems influence students every day, from the food that they eat to the air they breathe. In high school, students finally have enough understanding to explain patterns that they identified and asked questions about during their K–8 education. Some of these mechanisms occur in the blink of an eye while others take millions of years to unfold. Despite the extreme variability in scale, students have tools to use evidence, evaluate claims, and develop models to interpret the unseen. Students begin with phenomena and use them to enhance their understanding of core ideas in biological science and Earth and space sciences.

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 who 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. 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 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.

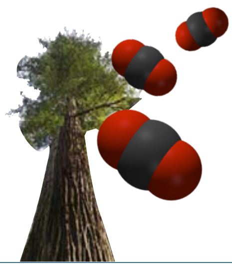
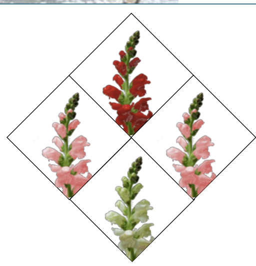
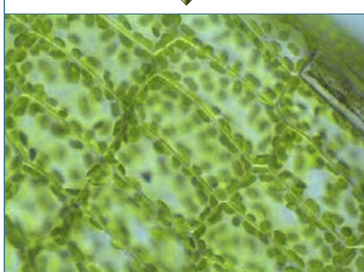
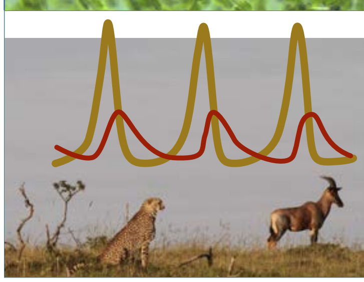
This example course is divided into instructional segments centered on questions about observations of a specific phenomenon. Different phenomena require different amounts of investigation to explore and understand, so each instructional segment should take a different fraction of the school year. As students achieve the performance expectations within the instructional segment, they uncover DCIs from life science and engineering. Students engage in multiple practices in each instructional segment, not only those explicitly indicated in the performance expectations. Students also focus on one or two 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 performance expectation, 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 or International Baccalaureate curriculum.

Example Course Mapping for an Integrated Life and Earth Science Course

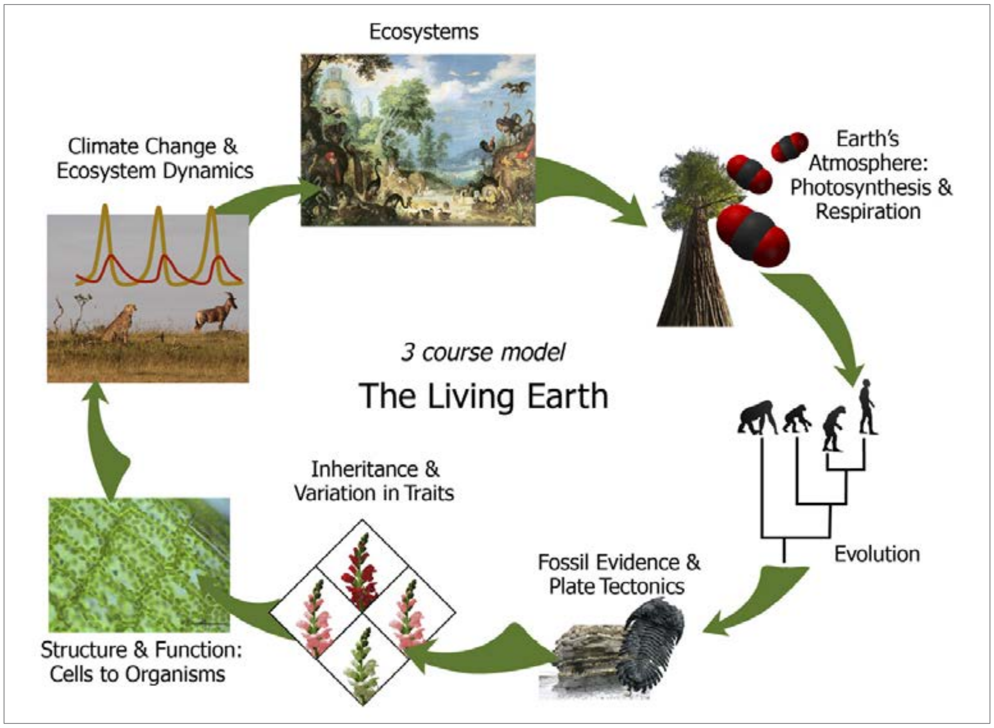
This section presents the life science and selected Earth science CA NGSS performance expectations organized into six embedded instructional segments (table 7.1). The sequence presented here spirals in scale (figure 7.1), starting with ecosystems as a whole (looking at both living and nonliving components), progressing into connections within ecosystems describing the cycling of matter in two important life processes: photosynthesis and respiration while also emphasizing the nonliving parts of these cycles. Then the course moves into evolution (in which evidence is based in both living and nonliving systems) and then links evolution to the study of heredity. From there the course zooms in more (progressing to smaller scales) to what defines characteristics of life from the cell to multicellular organisms. The course ends by coming back full circle to ecosystems and the impacts that humans have on them especially in relationship to climate change. A culminating project for this course should present a synthesis of how life on Earth is dependent on both biotic and abiotic factors.

Table 7.1. Overview of Instructional Segments for High School Three-Course Model Living Earth

	**1 Ecosystem Interactions and Energy** Students use mathematical and computer models to determine the factors that affect the size and diversity of populations in ecosystems, including the availability of resources and interactions between organisms.
	**2 History of Earth's Atmosphere: Photosynthesis and Respiration** Students make a model that links photosynthesis and respiration in organisms to cycles of energy and matter in the Earth system. They gather evidence about the linked history of Earth's biosphere and atmosphere.
	**3 Evidence of Evolution** Students develop a model about how rock layers record evidence of evolution as fossils. Building on their learning from previous grades, they focus on effectively communicating this evidence and relating it to principles of natural selection.
	**4 Inheritance of Traits** Students develop explanations about the specific mechanisms that enable parents to pass traits on to their offspring. They make claims about which processes give rise to variation in deoxyribonucleic acid (DNA) codes and calculate the probability that offspring will inherit traits from their parents.
	**5 Structure, Function, and Growth (from cells to organisms)** Students use models to create explanations of how cells use DNA to construct proteins, build biomass, reproduce, and create complex multicellular organisms. They investigate how these organisms maintain stability.
	**6 Ecosystem Stability & the Response to Climate Change** Students use computer models to investigate how Earth's systems respond to changes, including climate change. They make specific forecasts and design solutions to mitigate the impacts of these changes on the biosphere.

Sources: Savery 1628; adapted from Caulfield 2012; Grant 2010; adapted from Rafandalucia 2016; adapted from Castro 2008; Peters 2007; adapted from d'Alessio 2013

Figure 7.1. Conceptual Flow of Instructional Segments in Example High School Three-Course Model Living Earth



Sources: Savery 1628; adapted from Caulfield 2012; M. d'Alessio using image from Tkgd2007 2008; Grant 2010; adapted from Rafandalucia 2016; adapted from Castro 2008; Peters 2007; adapted from d'Alessio 2013

Long description of Figure 7.1.

IS1 Living Earth Instructional Segment 1: Ecosystem Interactions and Energy

An ecosystem is a biological system, and the first instructional segment (IS1) begins with a systems-based approach to ecosystems. Students focus on both biotic and abiotic conditions in a way that integrates life science and Earth and space science DCIs.

LIVING EARTH INSTRUCTIONAL SEGMENT 1: ECOSYSTEM INTERACTIONS AND ENERGY

Guiding Questions

- What factors affect the size of populations within an ecosystem?
- What are common threats to remaining natural ecosystems and biodiversity? How can these threats be reduced?

Performance Expectations

Students who demonstrate understanding can do the following:

HS-LS2-1. Use mathematical and/or computational representations to support explanations of factors that affect carrying capacity of ecosystems at different scales. [Clarification Statement: Emphasis is on quantitative analysis and comparison of the relationships among interdependent factors including boundaries, resources, climate, and competition. Examples of mathematical comparisons could include graphs, charts, histograms, and population changes gathered from simulations or historical data sets.] *[Assessment Boundary: Assessment does not include deriving mathematical equations to make comparisons.]*

HS-LS2-2. Use mathematical representations to support and revise explanations based on evidence about factors affecting biodiversity and populations in ecosystems of different scales. [Clarification Statement: Examples of mathematical representations include finding the average, determining trends, and using graphical comparisons of multiple sets of data.] *[Assessment Boundary: Assessment is limited to provided data.]*

HS-LS2-4. Use mathematical representations to support claims for the cycling of matter and flow of energy among organisms in an ecosystem. [Clarification Statement: Emphasis is on using a mathematical model of stored energy in biomass to describe the transfer of energy from one trophic level to another and that matter and energy are conserved as matter cycles and energy flows through ecosystems. Emphasis is on atoms and molecules such as carbon, oxygen, hydrogen and nitrogen being conserved as they move through an ecosystem.] *[Assessment Boundary: Assessment is limited to proportional reasoning to describe the cycling of matter and flow of energy.]*

HS-LS2-8. Evaluate the evidence for the role of group behavior on individual and species' chances to survive and reproduce. [Clarification Statement: Emphasis is on: (1) distinguishing between group and individual behavior, (2) identifying evidence supporting the outcomes of group behavior, and (3) developing logical and reasonable arguments based on evidence. Examples of group behaviors could include flocking, schooling, herding, and cooperative behaviors such as hunting, migrating, and swarming.]

HIGH SCHOOL THREE-COURSE MODEL LIVING EARTH INSTRUCTIONAL SEGMENT 1: ECOSYSTEM INTERACTIONS AND ENERGY

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-2] Developing and Using Models [SEP-5] Using Mathematics and Computational Thinking [SEP-7] Engaging in Argument from Evidence	LS2.A: Interdependent Relationships in Ecosystems LS2.C: Ecosystem Dynamics, Functioning, and Resilience LS2.D: Social Interactions and Group Behavior	[CCC-2] Cause and Effect: Mechanism and Explanation [CCC-3] Scale, Proportion, and Quantity [CCC-4] Systems and System Models [CCC-5] Energy and Matter: Flows, Cycles, and Conservation

Highlighted California Environmental Principles and Concepts:

Principle II The long-term functioning and health of terrestrial, freshwater, coastal and marine ecosystems are influenced by their relationships with human societies.

Principle IV The exchange of matter between natural systems and human societies affects the long-term functioning of both.

CA CCSS Math Connections: N-Q.1–3; S-ID.1; S-IC.1, 6; MP.2, MP.4

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

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

A **system [CCC-4]** includes component parts, interactions between those parts, and exchanges of **energy and matter [CCC-5]** to the world outside the system. Ecosystems contain living and non-living components that influence one another. In a way, an ecosystem is a microcosm of the entire Earth, with components that are so complicated it is often referred to as a system of systems. To help organize thinking about these sub-systems, scientists have divided up Earth materials and processes into five general groupings, each of which is shaped by its own internal workings and its interactions with the other **systems [CCC-4]**:

- Atmosphere: gases around the Earth (i.e., our air)
- Hydrosphere: all the water (sometimes ice is separated out into the cryosphere)
- Biosphere: all life

- Geosphere: inorganic rocks and minerals
- Anthrosphere: humanity and all of its creations (This sphere is not specifically mentioned in the *NRC Framework* [2012] because it is primarily part of the biosphere. Separating this sphere out emphasizes the significant influences humans have on the rest of Earth's systems and is consistent with California's EP&Cs).

This course centers on the biosphere and examines how it interacts with each of the other Earth systems. Teachers can introduce the biosphere by taking students to local ecosystems (either physically or virtually) to observe populations of plants and animals, to identify specific threats to biodiversity, and to consider alternative proposals to lessen those impacts. This local context can be a thread throughout the course.

Systems [CCC-4] are characterized by the **flow of energy and cycling of matter [CCC-5]** between their components. In the middle grades, students constructed models of these flows (MS-LS2-3), analyzed data about resource availability within a system (MS-LS2-1), and explained patterns in the way organisms interact (MS-LS2-2). This instructional segment builds on that understanding by using more detailed mathematical **models [SEP-2]** of ecosystems, including the sizes of different populations. Biologists use a specific definition of *population*: a group of individuals from the same species living together in the same geographical area at the same time.

Using **mathematical and computational thinking [SEP-5]** and **modeling [SEP-2]**, students can predict the effect certain interdependent factors have on the size of a population over time. The number of individuals within a population depends on birth rates, death rates, immigration, and emigration. Population growth rate is defined as the change in numbers of individuals (ΔN) divided by time (Δt). While some populations grow very quickly, populations cannot continue to grow exponentially forever. At some point they reach a maximum load that the environment they live in can support, called the *carrying capacity*. Students can use computer simulations[1] to **conduct investigations [SEP-3]** that test how different parameters **change [CCC-7]** population sizes, and then **analyze their findings [SEP-4]** (HS-LS2-1). Graphing their results, they can describe the population changes **mathematically [SEP-5]** (HS-LS2-2). Initially growth will be exponential, but students should be able to recognize the point on the graph where competition for resources begins to dramatically impact the population size.

1. There are many simulation/games available online that allow students to manipulate certain parameters that affect populations, example might be food resources or overcrowding.

Students can use simulations to recognize two general types of factors that limit population growth: Density-dependent factors and density-independent factors. Many factors are *density dependent*, such as food resources, space, nesting sites, and water, meaning that the amount of these resources required depends on the population size. *Density-independent* factors alter the number of individuals in a population regardless of how many individuals already exist. Instructional segment 1 focuses on density-dependent factors while IS6 introduces density-independent factors that often relate to interactions with other parts of the Earth system, such as weather pattern changes or catastrophic events like hurricanes, floods, landslides, volcanoes, etc. Nonetheless, introducing these two categories together can help students understand how **proportion and quantity [CCC-3]** are essential to describing density-dependent cases but not relevant in density-independent cases. Both density-dependent and density-independent factors affect the **flow of energy and matter [CCC-5]** within and into a system, which is ultimately the way in which they **affect [CCC-2]** the sizes of populations.

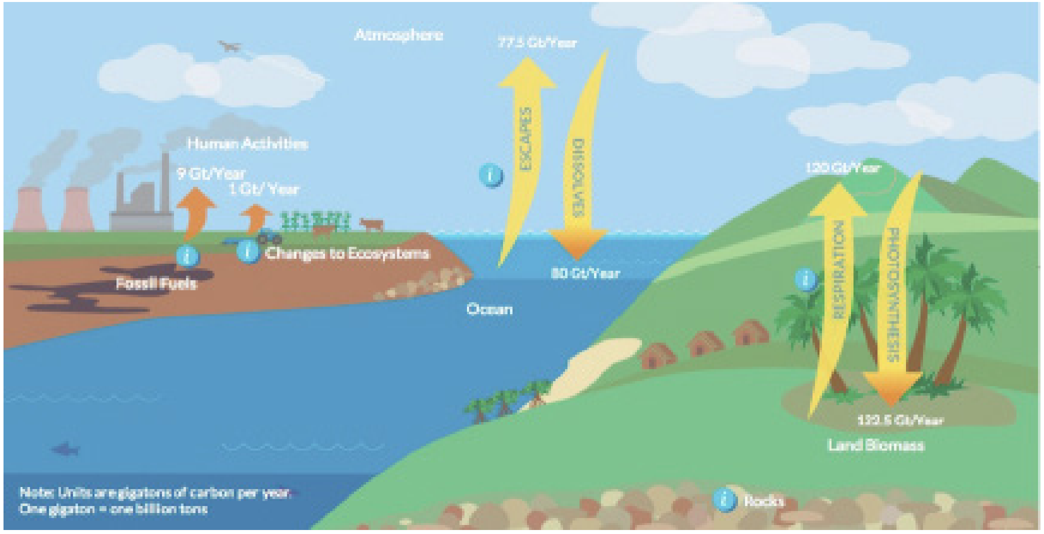
Many times, humans alter the availability of resources and change the landscape. For example, if a new freeway is built dividing a population's territory in half and limiting its migration, how will this cause both density-dependent and density-independent changes to the ecosystem? Human-induced changes to climate also cause changes to ecosystems. The Education and the Environment Initiative (EEI) Curriculum unit *Ecosystem Change in California,* which focuses on changes in a grassland ecosystem in the state provides guidance teaching EP&Cs II and IV as students obtain information about both the positive and negative ways humans influence ecosystem resources.

One of the resources organisms compete for is the food from which they obtain their energy. Organisms store potential energy within the chemical bonds of the matter in their bodies. As individual organisms grow and when populations become more plentiful, more total energy is stored. Biomass is the dry weight of all of the living organisms in an ecosystem and is related to the amount of energy available for these organisms. As a general rule, when an animal eats, it is only able to store about 10 percent of the energy from its food to build up its own energy stores. The rest of the energy is lost due to inefficient digestive processes or used in respiration to keep the animal alive long enough to eat again. As a result, each higher trophic level ends up with available energy that is just 10 percent the size of the level below it, creating a pyramid-like structure in population sizes with the lowest trophic levels at the base of the pyramid.

Using the conceptual **model [SEP-2]** of this energy pyramid, students find that very large populations of producers are required to support much smaller populations of tertiary consumers for the ecosystem to remain **stable [CCC-7]**. Mathematical **models [SEP-2]** use this principle to predict the size of a predator population given known populations of prey at other trophic levels. Students can explore many computer simulations and hands-on demonstrations so that they are able to support claims about the relative amounts of energy in different trophic levels (HS-LS2-4).

Energy flows from abiotic (nonliving forms) to biotic (living) forms, starting with sunlight or other light sources and inorganic compounds in producers and moving through consumers and decomposers. Nutrients (matter) cycle in the same manner. They can exist in forms that are largely abiotic, such as carbon dioxide (CO_2) and nitrogen (N_2), and move into living organisms (biotic) in a different form such as glucose ($C_6H_{12}O_6$) or starch (many joined glucoses) and nitrates (NO_3-). The movement from abiotic to biotic molecular forms involves living processes. For carbon (figure 7.2), these processes are photosynthesis and cellular respiration (discussed in IS2). For nitrogen, nitrogen-fixing bacteria change nitrogen gas into nitrates while bacterial decomposers change ammonia and nitrates back into nitrogen. In some cases, abiotic processes can do a similar job. When a lightning bolt travels through the atmosphere, its energy can break apart molecules of nitrogen in the air; free nitrogen atoms bond with oxygen to create nitrate that gets carried to the soil by raindrops. Other nutrients are involved in similar cycles (such as the phosphorous cycle as it relates to DNA or how climate change alters the calcium cycle and therefore affects hard-shelled marine organisms). Students can develop **models [SEP-2]** on paper, with technology, using their body moving around the room to represent the flow through different processes, or as a chemical model using organic chemistry molecule kits. The models show how simple inorganic molecules are made into larger organic molecules and then how they cycle back to the simple inorganic molecules.

Figure 7.2. The Carbon Cycle includes Biotic and Abiotic Processes



Source: WGBH n.d.
Long description of Figure 7.2.

While carbon and nitrogen are essential nutrients, toxic material also cycles through the ecosystem. Humans are major sources of disruptions to nutrient cycles, including adding toxins. Students can **obtain information [SEP-8]** about how mercury accumulates in certain fish species and learn about the impacts this can have on human health. Human activities such as operating coal power plants have added significant amounts of mercury to the environment (EP&Cs III and IV).

Up to this point, this instructional segment has considered how **flow of energy and matter [CCC-5]** moves between populations in an ecosystem and how that flow helps determine the size of a given population. Now, students zoom in and see how each population itself acts like a **system [CCC-4]** with interacting members. Students will look closely at the specific behaviors of populations that help those populations survive (HS-LS2-8). For a population to succeed and not become a genetic dead end, the gene pool (the set of all the different genes) of the population must be passed on to the next generation. Producing a new generation of healthy offspring capable of successful reproduction is important for a population's survival.

High School Three-Course Model Living Earth Snapshot 7.1: Does Living as a Group or Individual Help You Survive?

Anchoring phenomenon: Prairie dogs squeak and communicate to one another as they work together to fight off a snake that intrudes into their colony.

Mr. T started class showing a short video clip on prairie dogs and how they sound alarms to protect their family units against snakes (for example, NatGeoWild, Prairie Dog Snake Alarm: https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link3). He then asked the students to do a quickwrite on what behavior the prairie dogs used to protect themselves and how that behavior helped their family.

Later, the students played a game that was actually a physical **model [SEP-2]** of individual and group behavior. Students used their bodies to represent components in a **system [CCC-4]** with a predator-prey relationship. He needed an even number of students as prey; since Mr. T had 30 students, he designated two students to act as predators, leaving 28 students to act as prey. Mr. T randomly handed each prey a white index card that had a color code on it, with each color representing a different genotype. Mr. T set up the cards ahead of time so that there were four cards for each color (i.e., four blue cards, four yellow cards, four green cards, four red cards, etc.).

For the first round (prey living as individuals) the predators and prey did not have knowledge about the individual's genetics (in other words they did not know who was genetically related to whom). Mr. T instructed the 28 prey to randomly wander around the open area and after one minute he signaled the predators to attack. The predators then tagged a prey. That individual stepped out of the group and the rest of the students continued wandering; again Mr. T signaled for attack and again each predator tagged an individual who dropped out of the group. After seven attacks, half the prey (14 individuals) had been tagged. At that point, a recorder tallied all the colors left on a shared class spreadsheet showing how many of each genotype survived (for example, 0 blue, one yellow, etc.).

Then Mr. T assigned two different students to act as predators and told them to go sit in the corner and hide their eyes while he redistributed the index cards to the remaining 28 students who were again the prey. This time he told the prey students to quietly (so the predators don't know) find the other students who shared their color. These four students had the same genotypes and represented a kin group. The second round (altruistic prey in groups) began. Since Mr. T had a big open area, he blindfolded the predators. This was so they would not know about genotypes and relatives within the prey groups. The group units now randomly wandered in the space and again Mr. T signaled the predators to attack. Each kin group could surround an individual so that when they were tagged the individual prey was saved and did not get eliminated. Each genotype/color group received only one save in this round, after that save had been used, anyone

High School Three-Course Model Living Earth Snapshot 7.1: Does Living as a Group or Individual Help You Survive?

in the group who was tagged again, was eliminated. This rule is designed to simulate the cost to benefit ratio of altruism. Saving a member of your group incurs an individual cost because it means your group will not be able to save you during the next attack. The benefit is that the group to which you belong is more likely to survive as a whole. The game continued for a total of seven attacks. This time there were fewer than 14 individuals eliminated because some individuals were saved by the herding effect of their group. Then a recorder used the shared class spreadsheet to tally the number of individuals left in each color group.

Mr. T reassigned the roles of each student (picking new predators and shuffling the genotype cards) to prevent learning by predators. The class enacted each scenario one more time.

After the class completed the four rounds of the game, Mr. T had the students look at the whole class data that had been recorded. He defined the terms *individual fitness* (your ability to pass on your genes) and *inclusive fitness* (your individual fitness plus indirect fitness when you belong to a group that herds to save individuals). Mr. T then asked the students to use these terms to describe the similarities and differences they saw between the two scenarios and **explain [SEP-6]** how inclusive behavior (group behavior) could be advantageous for some populations (HS-LS2-8). Mr. T wanted the students to specifically address what the action of saving an individual meant in the altruistic group scenario. Students were expected to use examples of animals that they knew that used *inclusive fitness behaviors*. The students talked about the prairie dogs (as in the video), dolphin pods, rabbit colonies, bird flocks, monkey troops, and other social, family, or group behavior. Mr. T ended class with a video clip showing how water buffalo work as a group to counter-attack lions that have surrounded an individual water buffalo (for example, NatGeoWild, Buffalo Herd Counter Attack: https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link4). What was the individual fitness of the animal being attacked? How does its fitness change because of the behavior of the group?

The rest of this course zooms in to explain many of the mechanisms that drive the processes described in this instructional segment. At the end of the course (IS6), students will return to ecosystems and human impacts to revisit their models and address more complex ecosystem interactions. As preparation, IS1 can introduce the idea that urbanization, the building of dams, and dissemination of invasive species are active parts of the **flow of energy and cycling of matter [CCC-5]** within almost all ecosystems, even those that appear relatively undisturbed (EP&Cs II, IV).

IS2

Living Earth Instructional Segment 2: History of Earth's Atmosphere: Photosynthesis and Respiration

In the middle grades, students explained the role photosynthesis plays in cycling of matter by the production of sugars (food) using light energy and carbon dioxide (MS-LS1-6), and developed a model of how food molecules can be rearranged to extract usable energy (MS-LS1-7). They also are already familiar with cycles of matter within a system from their investigation of the water cycle (5-LS2-1, MS-ESS2-4). In this instructional segment, students explore the **cycling of matter [CCC-5]** between the biosphere and the rest of Earth's **systems [CCC-4]**.

LIVING EARTH INSTRUCTIONAL SEGMENT 2: EARTH'S ATMOSPHERE: PHOTOSYNTHESIS AND RESPIRATION

Guiding Questions

- How do living things acquire energy and matter for life?
- How do organisms store energy?
- How are photosynthesis and cellular respiration connected?
- How do organisms use the raw materials they ingest from the environment?
- How has the cycling of energy and matter changed over Earth's history?

Performance Expectations

Students who demonstrate understanding can do the following:

HS-LS1-5. Use a model to illustrate how photosynthesis transforms light energy into stored chemical energy. [Clarification Statement: Emphasis is on illustrating inputs and outputs of matter and the transfer and transformation of energy in photosynthesis by plants and other photosynthesizing organisms. Examples of models could include diagrams, chemical equations, and conceptual models.] *[Assessment Boundary: Assessment does not include specific biochemical steps.]*

HS-LS1-6. Construct and revise an explanation based on evidence for how carbon, hydrogen, and oxygen from sugar molecules may combine with other elements to form amino acids and/or other large carbon-based molecules. [Clarification Statement: Emphasis is on using evidence from models and simulations to support explanations.] *[Assessment Boundary: Assessment does not include the details of the specific chemical reactions or identification of macromolecules.]*

HS-LS1-7. Use a model to illustrate that cellular respiration is a chemical process whereby the bonds of food molecules and oxygen molecules are broken and the bonds in new compounds are formed resulting in a net transfer of energy. [Clarification Statement: Emphasis is on the conceptual understanding of the inputs and outputs of the process of cellular respiration.] *[Assessment Boundary: Assessment should not include identification of the steps or specific processes involved in cellular respiration.]*

LIVING EARTH INSTRUCTIONAL SEGMENT 2: EARTH'S ATMOSPHERE: PHOTOSYNTHESIS AND RESPIRATION

HS-LS2-3. Construct and revise an explanation based on evidence for the cycling of matter and flow of energy in aerobic and anaerobic conditions. [Clarification Statement: Emphasis is on conceptual understanding of the role of aerobic and anaerobic respiration in different environments.] *[Assessment Boundary: Assessment does not include the specific chemical processes of either aerobic or anaerobic respiration.]*

HS-LS2-5. Develop a model to illustrate the role of photosynthesis and cellular respiration in the cycling of carbon among the biosphere, atmosphere, hydrosphere, and geosphere. [Clarification Statement: Examples of models could include simulations and mathematical models.] *[Assessment Boundary: Assessment does not include the specific chemical steps of photosynthesis and respiration.]*

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.]

HS-ESS2-6. Develop a quantitative model to describe the cycling of carbon among the hydrosphere, atmosphere, geosphere, and biosphere. [Clarification Statement: **The carbon cycle is a property of the Earth system that arises from interactions among the hydrosphere, atmosphere, geosphere, and biosphere. (CA)** Emphasis is on modeling biogeochemical cycles that include the cycling of carbon through the ocean, atmosphere, soil, and biosphere (including humans), providing the foundation for living organisms.]

HS-ESS2-7. Construct an argument based on evidence about the simultaneous coevolution of Earth's systems and life on Earth. [Clarification Statement: Emphasis is on the dynamic causes, effects, and feedbacks between the biosphere and Earth's other systems, whereby geoscience factors control the evolution of life, which in turn continuously alters Earth's surface. Examples of include how photosynthetic life altered the atmosphere through the production of oxygen, which in turn increased weathering rates and allowed for the evolution of animal life; how microbial life on land increased the formation of soil, which in turn allowed for the evolution of land plants; or how the evolution of corals created reefs that altered patterns of erosion and deposition along coastlines and provided habitats for the evolution of new life forms.] *[Assessment Boundary: Assessment does not include a comprehensive understanding of the mechanisms of how the biosphere interacts with all of Earth's other systems.]*

HS-ESS3-6. Use a computational representation to illustrate the relationships among Earth systems and how those relationships are being modified due to human activity.* [Clarification Statement: Examples of Earth systems to be considered are the hydrosphere, atmosphere, cryosphere, geosphere, and/or biosphere. An example of the far-reaching impacts from a human activity is how an increase in atmospheric carbon dioxide results in an increase in photosynthetic biomass on land and an increase in ocean acidification, with resulting impacts on sea organism health and marine populations.] *[Assessment Boundary: Assessment does not include running computational representations but is limited to using the published results of scientific computational models.]* (Introduced but not fully assessed until IS6)

**LIVING EARTH INSTRUCTIONAL SEGMENT 2:
EARTH'S ATMOSPHERE: PHOTOSYNTHESIS AND RESPIRATION**

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-2] Developing and Using Models [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	LS1.C: Organization for Matter and Energy Flow in Organisms LS2.B: Cycles of Matter and Energy Transfer in Ecosystems PS1.C: Nuclear Processes PS3.D: Energy in Chemical Processes ESS2.D: Weather and Climate ESS2.E: Biogeology ESS3.D: Global Climate Change	[CCC-1] Patterns [CCC-4] Systems and System Models [CCC-5] Energy and Matter: Flows, Cycles, and Conservation [CCC-7] Stability and Change

Highlighted California Environmental Principles and Concepts:
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.

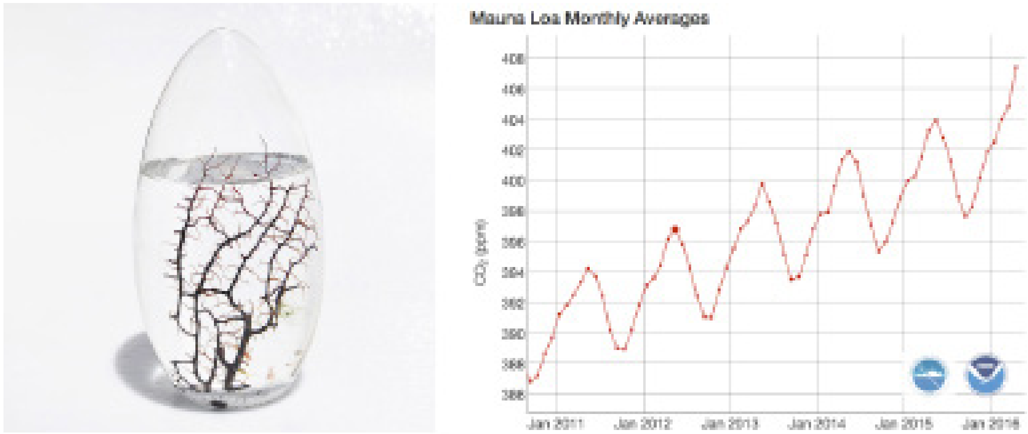
CA CCSS Math Connections: N-Q.1–3; F.IF.5; S-ID.6.a–c; MP.2, MP.4

CA CCSS for ELA/Literacy Connections: SL.11–12.5; RST.11–12.1; WHST.9–12.2a–e, 5, 8, 9

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

Students can consider the phenomenon of a sealed glass sphere that supports the survival and growth of both algae and brine shrimp (figure 7.3 left). How do they survive without air flowing in? On a more advanced level, they can observe how the global atmospheric CO_2 concentrations on Earth follow a distinctive **pattern [CCC-1]** each year (figure 7.3, right; because there is more land in the northern hemisphere and therefore more respiration during the growing season of the northern hemisphere summer). They should be able to explain and model each of these processes by the end of this instructional segment.

Figure 7.3. Phenomena Illustrating Relationship Between Photosynthesis and Respiration



A sealed sphere that supports survival of both brine shrimp and algae (left). CO_2 levels are highest in June each year and cycle annually (right). *Source*: Ecosphere Associates Inc. 2013 and National Oceanic and Atmospheric Administration (NOAA) 2016b

Long description of Figure 7.3.

All living organisms need energy, and high school students further refine an understanding that began in elementary school when they first traced energy in ecosystems back to plants and the Sun. Photosynthesis by producers involves two interdependent cellular processes: capturing sunlight/light energy by chloroplasts and using that energy to fix atmospheric carbon dioxide into glucose molecules. Plants either use the glucose directly or store energy by connecting glucose molecules together to form starch (which is easier to store).

Opportunities for ELA/ELD Connections

Working with a partner, students select a law of thermodynamics to research and then explain how energy is transferred and conserved and how energy can be harnessed to perform useful tasks. Each pair must research multiple print and digital sources, synthesize and summarize the key points, and present their findings using a visual display (e.g., poster, slides, handouts). The presentation should include a general description/definition of the law plus an example demonstrating the application of the principle.

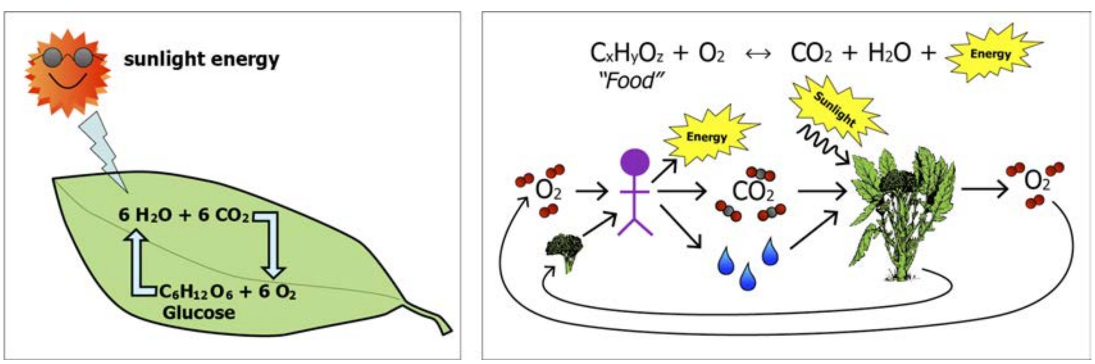
CA CCSS for ELA/Literacy Standards: RST.9–12.1, 2, 7, 9; WHST.9–12. 7, 8

CA ELD Standards: ELD.PI.9–12.6, 9

Heterotrophs (consumers or animals) ingest producers as food that they use for energy and building blocks for growth. Consumers often store energy in stacked glucose molecules in the form of glycogen (in higher animals, glycogen is stored in liver and muscle tissues). Both plants and animals use cellular respiration as the process by which organic molecules are broken down to release energy and form molecules of adenosine triphosphate (ATP). The process of cellular respiration uses up oxygen and releases carbon dioxide. The ATP formed in cellular respiration has high levels of potential energy that allow cells to do work; and therefore, if there is no ATP then there is no life. The energy from ATP is released when it is converted back into adenine diphosphate (ADP). Students do not need to know the individual biochemical steps of these two processes but rather need to understand the connections between them. Students will need to understand that these processes happen so that organisms can make ATP, the molecular source or currency of energy for the cell.

The products of photosynthesis are used as the reactants for cellular respiration and vice versa. Students can create **models [SEP-2]** of these processes using chemical equations or pictorial models that emphasize the **energy and matter [CCC-5]** inputs and outputs from each process (HS-LS1-5, HS-LS1-7; figure 7.4). Sometimes both processes occur in the same organism, and sometimes the respiration occurs in a consumer after it has eaten the producer. With each cycle of organisms eating or being eaten, there is less **usable** energy available to the organism (a consequence of the second law of thermodynamics, HS-PS3-4). In this way, ecosystems are constantly losing usable energy and therefore rely on the Sun to provide a constant influx of energy.

Figure 7.4. Models of Photosynthesis and Respiration



Two models showing how photosynthesis and respiration are mirrors of one another, involving the same basic ingredients. Matter cycles within the Earth system between the two processes, but energy must constantly flow in as sunlight to replace the energy put to work by organisms to grow and survive. Diagrams by M. d'Alessio and V. Vandergon
Long description of Figure 7.4.

Engineering Connection: Wastewater Treatment Facilities

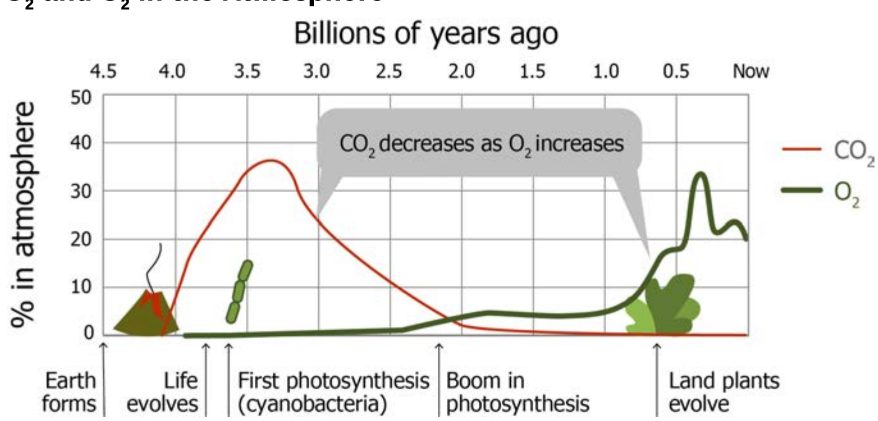
When raw sewage flows into waterways, it can impact the health of both humans and ecosystems (EP&Cs II, IV), which is why wastewater treatment facilities are an important part of all California cities. Engineers have learned to put biological processes to work to process human waste in wastewater treatment facilities. Students can **obtain information [SEP-8]** about the different stages of sewage treatment, some of which involve bacteria that rapidly decompose organic waste. Students can make physical **models [SEP-2]** of this process by using sugars to represent the organic waste, yeast to represent the waste-processing bacteria, and glucose test strips to measure the concentration of simulated waste in the water. Performing investigations using these models, students can develop techniques for speeding up the wastewater treatment process. Is there an optimal amount of yeast to add? Does the treatment process speed up or slow down when students add air or seal the container? What techniques can they develop for efficiently adding air? Students can **construct an explanation [SEP-6]** about how the change in oxygen in the bacteria's environment affects their respiration rate (HS-LS2-3).

A detailed model of photosynthesis and respiration can include the unique chemical properties of carbon. Carbon is structurally important to building all biological molecules, including the glucose molecule. What is so special about carbon? Carbon can covalently bond to four other atoms and forms single and double bonds with other atoms because of its electron structure and configuration. The same raw materials can be recombined in different configurations with different chemical potential energy, allowing carbon-based molecules to store or release energy during these changes. Students should be able to use computer simulations of this process to help them **construct explanations [SEP-6]** about how organisms build a wide range of organic molecules such as amino acids (HS-LS1-6).

Students can build a physical **model [SEP-2]** of a glucose molecule and show how to split it apart (with an emphasis on the components needed to build the glucose and the components left after the breakdown of the glucose). They should start with the atoms of carbon, hydrogen, and oxygen and make the simple molecules of CO_2, H_2O, and O_2 and then trace the movement of these molecules, much like they did in MS-LS1-7, but with added detail about what happens at each stage in the process. For example, the carbon dioxide and water are raw ingredients to photosynthesis and then are released as waste again in cellular respiration. CO_2's role in both processes means that photosynthesis and respiration are crucial parts of the global carbon cycle.

When did the **cycling of energy and matter [CCC-5]** start on Earth and how is cycling maintained? When asked what the Earth might have looked like 4.6 billion years ago when it first formed, students' *images* might be informed by prior knowledge that may include non-scientific sources and may not be consistent with the scientific understanding that Earth was lifeless. Teachers may need to explicitly discuss existing ideas and their sources before beginning instruction. When Earth first formed, its interior was still very hot and its interior rapidly convected (ties to HS-ESS2-3). Hot magma rising up is part of convection, so rapid convection caused volcanic activity in Earth's early history. When these volcanoes erupted, they released large amounts of gas that enriched our early atmosphere with CO_2. Around 3.4 billion years ago, organisms evolved that could perform photosynthesis, which disassembles CO_2. This marked the beginning of life's interaction with the global carbon cycle, an example of Earth's interacting **system [CCC-4]** of systems (biosphere interacts with atmosphere). In the CA NGSS, students must use evidence like the graph in figure 7.5 and their model of photosynthesis (HS-LS1-5) to **construct an argument [SEP-7]** that life has been an important influence on other components of the Earth system (HS-ESS2-7; HS-LS2-5). Early on, ocean water and chemical reactions with rock material absorbed much of the oxygen that plants produced. By examining records from rock layers, students can reconstruct aspects of Earth's early history (HS-ESS1-6). They can see evidence of biosphere-geosphere interactions in deep red colored rock layers called banded iron (because they are rich in iron oxides) that accumulated at the bottom of the ancient ocean. The oldest banded iron formations provide evidence of when plants first evolved, and thick deposits of banded iron about 2.4–1.9 billion years ago reveal another major **change [CCC-7]**—the expansion of multicellular cyanobacteria and a boom in photosynthesis.

Figure 7.5. CO_2 and O_2 in the Atmosphere



Concentrations of CO_2 and O_2 in Earth's atmosphere over its history. Dramatic changes happened as plants used CO_2 to grow biomass and released O_2 during photosynthesis. Diagram by M. d'Alessio, based on data from Holland 2006

[Long description of Figure 7.5.](#)

Examining the carbon cycle will help students understand how Earth **systems [CCC-4]** maintain life. The exchange of carbon between the atmosphere and the biosphere is just one of many important interactions between Earth's systems that involve the movement of carbon. In fact, one of the few additions that California made in adopting the CA NGSS was to add this sentence to the Clarification Statement for HS-ESS2-6: "The carbon cycle is a property of the Earth system that arises from interactions among the hydrosphere, atmosphere, geosphere, and biosphere." Scientists track the movement of carbon atoms through the carbon cycle much like they track the movement of water molecules through the water cycle. In both cases, scientists think about the **cycle of matter [CCC-5]** within a closed **system [CCC-4]** because at this point in Earth's history, very little water or carbon leaves the planet or arrives from space. We simply need to track the movement of the matter that is already here. A biological model of the carbon cycle is shown in IS1.

In the CA NGSS, students must develop a quantitative **model [SEP-2]** of the carbon cycle (HS-ESS2-6), which needs to include the following:

1. Places where carbon accumulates within the Earth system (called *reservoirs*, reminiscent of the storage of water in the water cycle)
2. Processes by which carbon can be exchanged within and between reservoirs (called *flows*)
3. The relative importance of these reservoirs and processes is based on the amount of carbon they hold or transfer

Various representations exist for the carbon cycle, including simple pictures like figure 7.2. Interactive animations (such as WGBH "Carbon Dioxide and the Carbon Cycle" https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link5), hands-on experiments (see OMSI "Experiment: Burning Issues" https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link6), and kinesthetic activities build on the static illustrations to help students develop conceptual **models [SEP-2]** of the reservoirs and processes by which carbon is exchanged between reservoirs. For example, students can develop a simple physical **model [SEP-2]** of the atmosphere-ocean **system [CCC-4]** by adding pH indicator to water in a closed container (see IS1 of the chemistry course). Students can use this model to **investigate [SEP-3]** what happens as a plant grows, a candle burns, or a person exhales through a straw into the water. They notice that pH changes as CO_2 from these sources interacts with the water to form carbonic acid. This same chemical reaction happens at the global scale with interactions between the atmosphere and the hydrosphere (PS1.B; IS6 of the chemistry course), making Earth's oceans one of the biggest reservoirs of carbon on the planet (see table 7.2 for the relative sizes of different reservoirs). Students will **explain [SEP-6]** how the concentration of CO_2 in the atmosphere affects the rate of a chemical reaction in HS-PS1-5 and the final concentration of acid in the ocean is an example of a system in equilibrium as explored in HS-PS1-6. Because the system is near equilibrium, massive amounts of carbon (about 80 gigatons) are absorbed into the ocean while massive amounts are also released back to the atmosphere. These opposite flows are similar in magnitude but do not balance out—the ocean absorbs about 2.5 gigatons per year more of carbon from the atmosphere than it releases back, causing the ocean to become more acidic. An acidic ocean can **cause [CCC-2]** major damage to plankton (that form the base of the ocean food chain, LS2.A, LS2.B) and coral reefs (which host a large portion of the ocean's biodiversity), both of which **affect [CCC-2]** sea life (LS3.C) (IS6 addresses human impacts). Scientists use complex computer models to calculate the expected changes in ocean chemistry based on different human activities, and the CA NGSS pushes students to use simple computer representations of **models [SEP-2]** to illustrate the relationships between different Earth **systems [CCC-4]** and **quantify [CCC-3]** how human activities change these systems (HS-ESS3-6; see IS6).

Table 7.2. Carbon Reservoirs and Atmospheric Flows

CARBON RESERVOIRS AND ATMOSPHERIC FLOWS			
RESERVOIR	**FORM OF CARBON**	**AMOUNT IN RESERVOIR**	**FLOW RATE WITH ATMOSPHERE**
Atmosphere	Mainly carbon dioxide (gas)	840 Gt	Greenhouse gases are increasing due to human activities.
Biomass (*biosphere*)	Sugar, protein, etc. (solid, liquid)	2,500 Gt (mostly in plants and soil)	About 120 Gt per year into and out of air. Currently absorbing about 2.5 Gt per year
Ocean (*hydrosphere*)	Mostly dissolved bicarbonate salts	41,000 Gt	About 80 Gt per year into and out of air. Currently absorbing about 2.5 Gt per year
Sedimentary rocks (*geosphere*)	Carbonate minerals (solid)	60,000,000 Gt	Negligible annually but important over very long time scales.
Fossil Fuels (*geosphere/ anthrosphere*)	Methane (gas) Petroleum (liquid) Coal (solid)	10,000,000 Gt	About 9 Gt per year into atmosphere, mostly from burning as fuels for energy.
Units are Gigatons (Gt) of carbon. 1 Gt = 1 billion tons			

Table by Dr. Art Sussman, courtesy of WestEd

Table 7.2 also reveals that the single largest reservoir of carbon is not in the air or water, but in rocks. How does it get there? After students learn about the chemical composition of life (LS1.C), they are able to explain why carbon is so important for so many of life's **systems [CCC-4]** (HS-LS1-6). Living organisms are therefore a large reservoir of carbon. When those organisms die, the carbon stored in their bodies can accumulate in layers that are buried over geologic time (discussed more in IS3). Heat and pressure, caused by burial, speed up chemical reactions that slowly reorganize the carbon and other elements into new, easily combustible molecules that we call fossil fuels, including oil (petroleum) and natural gas (including methane). To ensure that students see the connection between past life and oil formation, students can draw the stages of oil formation to summarize an article (The National Energy Education Development Project 2012, 13, 57). Extracting oil and gas from deep within the Earth and burning it harnesses energy that ancient plants and animals collected millions of years ago and that has been stored as chemical potential energy in materials trapped underground for millions of years. These materials are incredibly valuable for generating electricity, fueling our vehicles, and generally enabling modern society to thrive. Unfortunately, fossil fuels form very slowly and only under specific conditions and therefore are considered non-renewable because we consume them more quickly than they form. Access to fossil fuels occurs in specific places on Earth and California has large deposits, though extracting them can often leak or spill toxic chemicals into the air, land, and water (EP&C II, IV). While they are very convenient (EP&C V), they also disrupt the natural carbon cycle (EP&C III). Students weigh the cost and benefits of these fuels in the Physics of the Universe course.

IS3 Living Earth Instructional Segment 3: Evidence of Common Ancestry and Diversity

Evolutionary scientist Theodor Dobzhansky made the now famous quote, “Nothing in biology makes sense except in the light of evolution.” Therefore, one option is for evolution to occur early in this course and much of the rest of the course explains the detailed mechanisms that **cause [CCC-2]** the **patterns [CCC-1]** introduced in this instructional segment.

LIVING EARTH INSTRUCTIONAL SEGMENT 3: EVIDENCE OF COMMON ANCESTRY AND DIVERSITY

Guiding Questions

- How do layers of rock form and how do they contain fossils?
- Why do we see similar fossils across the world from each other but living organisms that are very different?
- What evidence shows that different species are related?
- How did modern day humans evolve?

Performance Expectations

Students who demonstrate understanding can do the following:

HS-LS4-1. Communicate scientific information that common ancestry and biological evolution are supported by multiple lines of empirical evidence. [Clarification Statement: Emphasis is on a conceptual understanding of the role each line of evidence has relating to common ancestry and biological evolution. Examples of evidence could include similarities in DNA sequences, anatomical structures, and order of appearance of structures in embryological development.]

HS-LS4-2. Construct an explanation based on evidence that the process of evolution primarily results from four factors: (1) the potential for a species to increase in number, (2) the heritable genetic variation of individuals in a species due to mutation and sexual reproduction, (3) competition for limited resources, and (4) the proliferation of those organisms that are better able to survive and reproduce in the environment. [Clarification Statement: Emphasis is on using evidence to explain the influence each of the four factors has on number of organisms, behaviors, morphology, or physiology in terms of ability to compete for limited resources and subsequent survival of individuals and adaptation of species. Examples of evidence could include mathematical models such as simple distribution graphs and proportional reasoning.] *[Assessment Boundary: Assessment does not include other mechanisms of evolution, such as genetic drift, gene flow through migration, and co-evolution.]*

HS-LS4-4. Construct an explanation based on evidence for how natural selection leads to adaptation of populations. [Clarification Statement: Emphasis is on using data to provide evidence for how specific biotic and abiotic differences in ecosystems (such as ranges of seasonal temperature, long-term climate change, acidity, light, geographic barriers, or evolution of other organisms) contribute to a change in gene frequency over time, leading to adaptation of populations.].

HS-LS4-5. Evaluate the evidence supporting claims that changes in environmental conditions may result in: (1) increases in the number of individuals of some species, (2) the emergence of new species over time, and (3) the extinction of other species. [Clarification Statement: Emphasis is on determining cause and effect relationships for how changes to the environment such as deforestation, fishing, application of fertilizers, drought, flood, and the rate of change of the environment affect distribution or disappearance of traits in species.]

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.

LIVING EARTH INSTRUCTIONAL SEGMENT 3: EVIDENCE OF COMMON ANCESTRY AND DIVERSITY

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).] (Introduced, but assessed in High School Chemistry in the Earth System course)

HS-ESS2-5. Plan and conduct an investigation of the properties of water and its effects on Earth materials and surface processes. [Clarification Statement: Emphasis is on mechanical and chemical investigations with water and a variety of solid materials to provide the evidence for connections between the hydrologic cycle and system interactions commonly known as the rock cycle. Examples of mechanical investigations include stream transportation and deposition using a stream table, erosion using variations in soil moisture content, or frost wedging by the expansion of water as it freezes. Examples of chemical investigations include chemical weathering and recrystallization (by testing the solubility of different materials) or melt generation (by examining how water lowers the melting temperature of most solids).]

HS-ESS3-1. Construct an explanation based on evidence for how the availability of natural resources, occurrence of natural hazards, and changes in climate have influenced human activity. [Clarification Statement: Examples of key natural resources include access to fresh water (such as rivers, lakes, and groundwater), regions of fertile soils such as river deltas, and high concentrations of minerals and fossil fuels. Examples of natural hazards can be from interior processes (such as volcanic eruptions and earthquakes), surface processes (such as tsunamis, mass wasting, and soil erosion), and severe weather (such as hurricanes, floods, and droughts). Examples of the results of changes in climate that can affect populations or drive mass migrations include changes to sea level, regional patterns of temperature and precipitation, and the types of crops and livestock that can be raised.]

HS-ESS3-4. Evaluate or refine a technological solution that reduces impacts of human activities on natural systems.* [Clarification Statement: Examples of data on the impacts of human activities could include the quantities and types of pollutants released, changes to biomass and species diversity, or areal changes in land surface use (such as for urban development, agriculture and livestock, or surface mining). Examples for limiting future impacts could range from local efforts (such as reducing, reusing, and recycling resources) to large-scale geoengineering design solutions (such as altering global temperatures by making large changes to the atmosphere or ocean).]

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.

LIVING EARTH INSTRUCTIONAL SEGMENT 3: EVIDENCE OF COMMON ANCESTRY AND DIVERSITY

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-3] Planning and Carrying Out Investigations [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	LS4.A: Evidence of Common Ancestry and Diversity LS4.B: Natural Selection LS4.C: Adaptation ESS2.B: Plate Tectonics and Large-Scale System Interactions ESS2.C: The Roles of Water in Earth's Surface Processes ESS3.A: Natural Resources ESS3.B: Natural Hazards ESS3.C: Human Impacts on Earth Systems PS1.C: Nuclear Processes ETS1.B: Developing Possible Solutions	[CCC-1] Patterns [CCC-2] Cause and Effect: Mechanism and Explanation [CCC-6] Structure and Function [CCC-7] Stability and Change

Highlighted California Environmental Principles and 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 CCSS for ELA/Literacy Connections: SL.11–12.4; RST.11–12.1, 8; WHST.9–12.2.a–e, 7, 9

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

To understand the evidence for how evolution has shaped life over time, students need to think about processes in both the biosphere and geosphere. Students need to understand more about fossils so that they will be able to interpret fossil evidence of evolution.

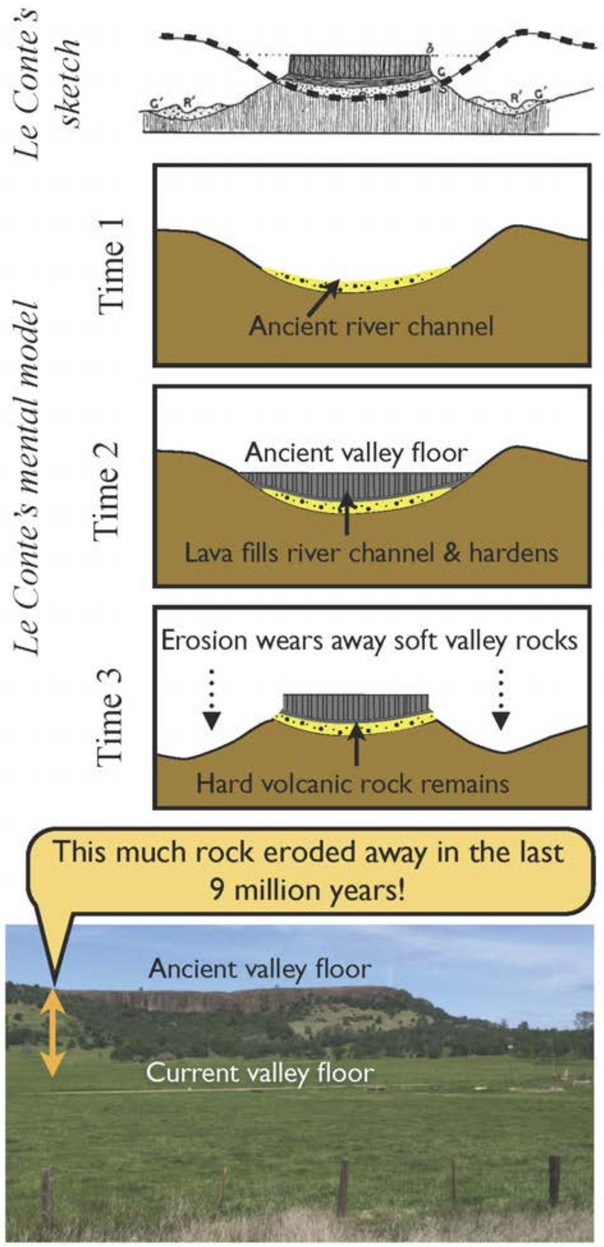
Fossils as a Part of the Geosphere

Evolution requires changes that span many generations of a population, so it can only be directly observed in populations that reproduce very quickly such as bacteria in petri dishes. For the rest of organisms, scientists have sought out other lines of evidence. In particular, the fossil record allows them to peer back over a very long time interval and discover transitional life forms, indications of organisms that no longer exist, and the absence of fossils of modern species in very old sediments. Finding of fossils in layers of deep valleys or mountaintops leads to questions about how fossils form and are preserved for millions of years. This instructional segment begins with students developing models of the ways that the rock record records past events.

Just as evolution changes populations, a variety of processes shape the physical landscape on Earth. What evidence do these processes leave behind? In the 1850s, geologists in California like Joseph Le Conte, one of the first faculty members at the University of California, began to look at landscapes and construct mental models of how landscapes developed and changed by erosion (figure 7.6). These mental models required testing, so Earth scientists conducted small experiments of erosion in laboratories. A stream table (a sloped table or plastic bin covered with sand and other earth materials and flooded with water) is a platform for exploring erosional processes; it can be used for hands-on **investigation [SEP-3]** and as a physical, conceptual **model [SEP-2]** that can predict possible outcomes. Teachers can use stream tables to help meet some of the performance expectations of the CA NGSS, including having students **ask questions [SEP-1]** and plan their own **investigations [SEP-3]** (HS-ESS2-5). Students can recreate California landforms such as the Sierra Nevada and Central Valley in a stream table and watch as sediment slowly accumulates in deep layers in the Valley. These sediments are rich in nutrients, so students can construct an **explanation [SEP-6]** of how erosion has fueled the California agricultural economy (HS-ESS3-1). Or students can be given a range of materials to see if they can produce the mesa-like features of Table Mountain. With this hands-on experience, students should be able to **explain [SEP-6]** why there are layers of rock and how those layers are deposited and accumulate over time.

Each layer that is deposited preserves a record of what the physical environment was like at the time. Even after the climate of the region has changed and millions of years have passed, we get a glimpse of what the ecosystem was like at this spot because the ancient river channel in Time 1 of figure 7.6 may preserve fossils of organisms that once drank from or swam in it. Like a little time capsule, the solid cap of lava protected these fossils from erosion.

Figure 7.6. Tuolumne Table Mountain Near Jamestown



Tuolumne Table Mountain near Jamestown, CA reveals how much soil and rock has eroded. Joseph LeConte sketched the drawing on the top for a textbook he wrote in 1882. LeConte was one of the first faculty at the University of California and a charter member of the Sierra Club. There are several schools in California named after him, including ones in Los Angeles and Berkeley. *Source*: LeConte 1892; photo by Kirk Brown; illustration by M. d'Alessio
Long description of Figure 7.6.

The process of lava capping a layer is far less common than simply having layers of sediment deposited one on top of the other. The constant buildup of layers like in the Grand Canyon is the geologic example of **structure and function [CCC-6]**. In biology, the shape of objects gives clues about what they are used for, while in geology the shape of the landscape reveals the process that brought it into existence. Sedimentary rock layers tell us that material was eroded from one area and deposited in another, usually driven by water, wind, or gravity. Details about the layers and the arrangement of the materials in them (the structure) reveal clues about the ancient environment such as the past climate because it affects the amount and speed of the water and the intensity of the wind (the function).

While people often think of erosion and deposition as slow and steady processes, these processes are often much more dramatic, which turns out to be important for fossil preservation. Students can observe the rate for themselves in a stream table where slow and steady erosion is punctuated by rapid landslides. The slow movement of sediment from the base of a cliff eventually hits a critical point and a massive piece of the cliff suddenly falls. The erosion rate then slows down because the cliff erodes into a flatter hillslope. California's coastal bluffs repeatedly face this problem, often eroding many feet in a single storm and then remaining **stable [CCC-7]** for decades. Students can **investigate [SEP-3]** actual coastal erosion rates using online collections of historical photos as found in Google Earth and the California Coastal Record to measure the impact of waves on the coastline (HS-ESS2-5).

Figure 7.7 shows oblique aerial photos of Pacifica, California, but the aerial photos in Google Earth are precise enough that students can measure the amount of coastline erosion as a classroom experiment. Such sudden land failures can preserve fossils because they immediately cover and protect remains of entire organisms, rather than allowing them to be torn apart by scavengers. For example, famous dinosaur fossils of two dinosaurs fighting (for example, see American Museum of Natural History, Fighting Dinos exhibition notes, https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link7) or mother dinosaurs sitting on nests of eggs are only possible because some depositional event covered them quickly. Even in places like the middle of the open ocean where there are no dramatic events like landslides, there are seasonal, decadal, and longer-term variations producing changes in deposition rates that are recorded by the layers of rock. Processes that appear to occur at a **stable [CCC-7]**, constant rate may actually be periodically **changing [CCC-7]** when viewed at the right **timescale [CCC-3]**.

Figure 7.7. Coastal Bluff Changes Over Time

Changes over time in coastal bluffs in Pacifica California. They go for many years without much erosion and then erode more than a dozen feet in a single year. The yellow arrow shows the migration of the cliff top from year to year at a single position. By 2010, the cliff is located directly beside the apartment building. *Source*: California Coastal Records Project 2017. Copyright © 2002–2015 Kenneth & Gabrielle Adelman, California Coastal Records Project, www.californiacoastline.org
Long description of Figure 7.7.

Engineering Connection: Coastline Erosion

When coastline erosion affects humans, it becomes a natural hazard. Students can explain some of the common impacts of erosion in California (HS-ESS3-1). They can also engage in an engineering design problem to reduce these impacts (HS-ESS3-4). Students can design and build erosion control measures using stream tables as well as read about actual measures that are taken in places like Pacifica and locations all along the California coastline. The engineering solutions either involve (1) increasing the strength of the hillside (by adding plants with root systems to stabilize the hillside, building support walls, or covering the cliff with concrete); or (2) reducing the driving forces (by placing rocks or sea walls to reduce the speed of waves when they hit the natural hillslope and through better drainage). Students should compare and evaluate solutions based on prioritized criteria and tradeoffs that account for a range of constraints, including cost, safety, reliability, and aesthetics. (HS-ETS1-3; EP&C V). Sometimes, technologies that reduce the impact of erosion on people can have adverse impacts on ecosystems (EP&C III). Students should consider and evaluate the environmental impacts of their design and refine it to reduce those impacts (HS-ESS3-4). Students can **obtain information [SEP-8]** about different California coastal communities and **explain [SEP-6]** why they have chosen to develop or not develop their coastlines (HS-ESS3-1).

With a better understanding of how Earth's geosphere changes at the surface, students are better equipped to interpret the fossil record. Because fossils are recorded in rock layers piled one on top of another, geologists look back in time as they dig deeper. Sequences of layers reveal a sequence of time like pages in a book (as students discovered in the middle grades with MS-ESS1-4). In this way, scientists can examine fossils and look at how organisms change over time.

Evidence for Evolution

Students can begin by obtaining examples of evidence supporting evolution that they learned about in the middle grades: patterns in fossils (MS-LS4-1), anatomical similarities (MS-LS4-2), and embryological similarities (MS-LS4-3). In each case, they can find more detailed evidence. The goal for high school is to have enough conceptual understanding to communicate these lines of evidence effectively. To help students meet HS-LS4-1, curriculum can focus on the SEP of **communicating information [SEP-8]**, which includes writing, oral presentations, and especially visual displays (diagrams, charts, annotated photos, etc.). Students can compare multiple depictions and **evaluate [SEP-8]** which ones illustrate the common ancestry most effectively. What are the elements of an effective communications product?

The fossil record provides much of the evidence to support evolution because it includes transitional life forms as well as organisms that no longer exist. In addition, many life forms alive today (including humans) are not found very far back in the fossil record, implying that they are newer and therefore evolved from other species. Effective communication of this evidence shows progressions of species and identifies where species appear or disappear in the fossil record.

Looking at structures that are *homologous* (features that originate from the same structure within a common ancestor) and *analogous* (features that arise because two species use a similar structure to accomplish the same function) also provides evidence of how, over time, parts of organisms have changed in both **structure and function [CCC-6]**. Effective communication of this evidence shows comparisons of structures side-by-side and highlights the similarities.

Students can look at a variety of skeletons of vertebrates from the major classes and identify **patterns [CCC-1]**, noting that all these animals share the same basic skeletal structure but with only small variations such as the placement and usage of forelimbs or hind limbs. For example, a dog foreleg, human arm, and seal forelimb are all forelimbs of mammals (homologous) but serve very different functions (so they are not analogous). On the other hand, a dog and a horse have homologous forelimbs that they both use to walk. Students should be able to **construct arguments [SEP-7]** that two organisms share a common ancestor using homologous structures as evidence. Similarly, they should use the observation that homologous structures are used in diverse ways as evidence that natural selection accentuates certain favorable traits over generations, leading to a gradual evolution.

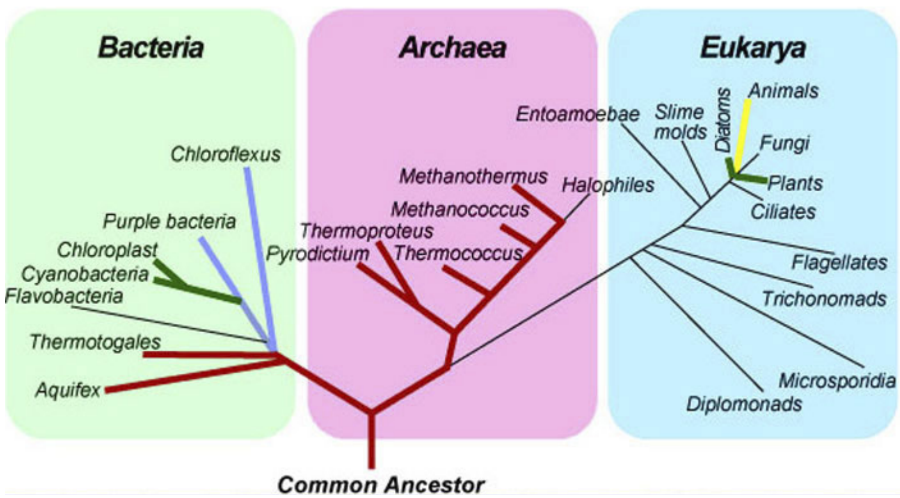
Are all structures with similar functions caused by genetic similarity and common ancestry? In high school, students develop a nuanced understanding of **cause and effect [CCC-2]** when they evaluate evidence to determine which cause (or causes) most likely explains a given observation. For example, penguins and dolphins both have streamlined bodies that allow them to swim efficiently. This feature is not the result of common ancestry, but rather an example of convergent evolution. Both these organisms independently evolved their body shapes from separate ancestors. Students can identify examples from the plant kingdom as well. The modified leaves in a Venus flytrap and pitcher plant demonstrate a homologous trait used to help the plants catch insects (all of these plants share a common ancestor). Thorns and spines, however, are a common analogous trait that protects plants from herbivores; this trait evolved in a wide range of plants through convergent evolution. As students **develop arguments [SEP-7]** that two organisms share common ancestry, they need to consider whether to present evidence of homology, analogy, both, or neither.

Because of the changes in organisms over time, some organs/structures no longer have a use in the modern day organism, although there is evidence that the structure was once functional in the ancestor; these traits are now called vestigial organs/structures. Some classic examples of *vestigial organs/structures* are the remnants of hipbones in snakes and whales and the remainder of the tip of a tailbone (the coccyx) in humans.

Evolution itself is not a linear process, but rather a branching process in which the members of populations of an ancient species change and branch into two new descendant species from a common ancestor (see IS6). These descendent species underwent more changes and could have possibly branched again and again over geological time. Visual depictions of this tree of life (figure 7.8) summarize our understanding of how life evolved from single-cell organisms to the modern species we see on earth today. The tips of the tree represent these modern species. These trees were developed using studies of fossils and have been refined using investigations of the similarities and differences in DNA. What makes these diagrams effective at communicating evolutionary history? How can they be improved?

Students should be able to **communicate [SEP-8]** evidence both graphically and in writing. Students can design Venn diagrams or tables to communicate commonalities and differences. They will have to revisit these comparisons later in the course as they add information about the common structure of DNA, cell structures, the process of cell division, etc.

Figure 7.8. Tree of Life



A tree diagram showing the relationship of all living species on Earth. All branches relate to the common ancestor at the base, which diverged into three main branches: bacteria, microbes known as Archaea, and a group of multicellular organisms called Eukarya, which includes humans. Longer branches indicate a more significant change in DNA from its common ancestor. *Source*: Farmer 2000
Long description of Figure 7.8.

Living Earth Snapshot 7.2: Simulating Evolution of Antibiotic-Resistant Bacteria

Everyday phenomenon: When you get a prescription antibiotic from the pharmacy, the symptoms go away in a few days but the instructions always say to keep taking the drug for as long as two weeks.

Mr. K asked students if they had ever had an ear infection and had to take antibiotics. Did they have a nasty tasting liquid or a huge pill to swallow? But did they get better? How long did it take? He then asked them if they remember how long they took the medicine. He passed around an empty antibiotic bottle (with patient information removed) and projected a picture of the label on the screen so that everyone could see how long the instructions say to take the drug. Could they just stop taking the antibiotic when they start feeling better?

Investigative phenomenon: Bacteria can become resistant to antibacterial drugs.

Evolution appears to be slow because **changes [CCC-7]** happen in populations over many, many generations. Bacteria reproduce every few hours, so humans can actually observe their evolution. Mr. K's class simulated the effects of antibiotics on bacteria populations using colored index cards or foam packing peanuts (NSTA https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link8). Each index card represented an individual bacteria organism; most cards were white, but two red cards represented individuals of the same species that were somehow resistant to the antibiotic. During each round, an antibiotic was applied that killed three out of four of the white cards but none of the resistant red cards. After each round, the bacteria reproduced, so students collected another card of the same color. Students graphed the number of bacteria and identified the **trend [CCC-1]** that the population had evolved to become resistant to antibiotics.

Mr. K asked students to formulate the rules of the index card game as a **computational algorithm [SEP-5]**. Students then wrote their own computer code and used it to predict what happened to the population of bacteria when a person with an infection stopped taking antibiotics before the end of the prescription. They culminated by constructing an **explanation [SEP-6]** about how the use of antibacterial agents can cause bacteria to evolve into superbugs (HS-LS4-4). They watched a video to **obtain information [SEP-8]** about how resistant bacteria are impacting behaviors and health at local hospitals. Mr. K then pretended to be one student's father who wanted to throw out his antibiotic when his symptoms went away but before the prescription ended. He asked the student to **convince him using evidence [SEP-7]** that he should keep taking the medication.

As students recognize the lines of **evidence [SEP-7]** supporting evolution they can connect it to what Charles Darwin postulated in the middle 1800s. Darwin spent his adult life collecting and analyzing data. Interestingly, he was a naturalist on a boat expedition (HMS Beagle) that was sailing the world to map landforms and geologists on this same expedition (and others like it) would contribute data to our understanding of plate tectonics (see below). The result of Darwin's work is the foundation for the study of evolution. What Darwin noticed was that organisms have the potential to reproduce many more offspring (for example, a spider will lay hundreds of eggs) than will survive. He noticed that despite the potential for large numbers in a population most populations remain fairly constant in numbers over generations. Darwin concluded that there had to be competition for resources and that is part of what helped keep population numbers stable over time. He also noticed that while fossils and modern living organisms differed from place to place, the fossils and modern living organisms in the same area were very similar to one another. For example, Darwin saw that several bird species in the Galápagos Islands looked very similar to one species found on the continent of nearby South America. He also knew that offspring looked like their parents but there was slight variation. He understood how animal breeders manipulate the traits in the population of their livestock or dogs by selectively breeding to reinforce or eliminate certain traits. All these observations helped him frame the Theory of Natural Selection, which states that there is competition over resources and the individuals in a population that can get the resources they need are able to reproduce and pass on their traits to their offspring and therefore are the more fit individuals of the population. If no individuals reproduce, then that population ceases to exist and any unique alleles within that population are also eliminated. Darwin originally summarized his findings into four postulates (table 7.3).

Table 7.3. Darwin's Four Postulates

DARWIN'S POSTULATE	EXAMPLE
Individual organisms in a population vary in the traits they possess.	The size of their heads or the length of a taproot
Some of this variation is passed from parent to offspring.	Seeds from plants with purple flowers grow into new plants with purple flowers; insects with long wings produce offspring with long wings.
Individuals within a population have the ability to produce a lot of offspring.	Number of seeds produced by a flowering tree, the ability of some bacteria to reproduce every 20 minutes, the number of spores released by a mushroom.

DARWIN'S POSTULATE	EXAMPLE
The individuals that leave living offspring are the individuals with certain traits that help them survive and reproduce, thus they are the individuals that are selected naturally by the environment.	Birds that can break open nuts that grew harder in a drought year could acquire enough food and survive the environmental change (drought) so they then could go on to reproduce.

Students should observe examples of evolution in all living systems (e.g., plants, fungi, animals, prokaryotes, etc.). Students can collect data on individuals in a population and look for the **patterns [CCC-1]** that are present. They can measure individual skulls or beaks or shells that have been gathered to represent a specific species. There are datasets available that extend from generation to generation (HHMI 2014; Grant and Grant 2014) and students can use these to mathematically **analyze [SEP-4]** the changes they observe. They can begin to **construct an explanation [SEP-6]** based on this evidence of the conditions that are necessary for evolution to occur (HS-LS4-2). Extensions of this data collection can include some generations that survived after a change in their environment (e.g., what happens to the size of beaks after a drought or what happens to the size of shells after the introduction of a non-native species that eats the shelled organism). From these observations, students notice that interactions in the environment influence evolution (EP&Cs I, II). The vignette in IS6 provides an example of this sort of data analysis.

Ideally, students should do an in-depth investigation of one species and obtain information about the evidence of its evolutionary history. One possible example is the history of modern humans (the vignette in IS6 illustrates another). Using genome studies on DNA sequences as well as fossil evidence, scientists estimate that the common ancestor for humans and great apes lived over seven million years ago. Since that time, each branch has undergone further evolution. Students can use interactive tools to examine fossils and arrange them on a timeline based on **patterns [CCC-1]** that document human evolution.[2] How exactly did these changes happen?

2. HHMI-Howard Hughes Medical Institute http://www.cde.ca.gov/ci/sc/cf/ch7.asp#link165. This Web site is free, kept up to date, and has excellent resources for evolution as well as other science topics designed by experts in the field for use by teachers and students.

High School Three-Course Model Living Earth Snapshot 7.3: Human Evolution

Anchoring phenomenon: Several other species of hominin existed, but our species, *homo sapiens*, is the only one that survived to today.

Evolution is driven by natural selection favoring some new traits over others. But which new traits or selective pressures allowed our species, *Homo sapiens*, to thrive while several other early hominin species died off? Mrs. B recently saw the September 2014 issue of *Scientific American* https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link9) that addresses that very question. Each article offers a different argument supported by different evidence. One article focuses on specific anatomical features (*structure and function, LS1.A*), several articles on group behavior (LS2.D) including mating for life, cooperative hunting, and the power of culture, one article on information processing (LS1.D), and one article emphasizes the role of ancient climate change on evolution (ESS2.E, ESS3.D).

Mrs. B assigned different students to read different articles in a classic jigsaw. Then she organized the students so that each group discussed a common article. Each student group created a collaborative presentation about its article that summarized the argument made in the paper. Students had to identify the claim, describe the evidence, and tie it all together with reasoning. The students needed to pay particular attention to fossil evidence (ESS1.C), which was described more in some articles than others. Then, the student groups were reorganized, with one expert on each article in each group. Each expert presented the collaborative presentation about the article to his or her small group. Then, the group laid out a large sheet of butcher paper and created a comprehensive concept map illustrating the possible explanations of how humans evolved and then connected those explanations to other key course ideas. For example, students knew that the pace of present-day climate change is much faster than a climate shift 160,000 years ago that one article mentioned may have been a selective pressure that favored larger brains. It is unlikely that humans or other species can adapt quickly enough to keep pace with modern changes happening on the scale of decades. Mrs. B emphasized the fact that today we do not have enough evidence to distinguish between these different possibilities, but one day somebody might discover key evidence that allows us to rule out some of the possibilities or provides direct evidence of a cause and effect relationship for others. Mrs. B added, “And the person who will make that discovery might be in this room right now.”

Isolated Species as Evidence of Plate Tectonics

When scientists around the world collected fossils that showed evidence of systematic progressions of species within the biosphere, they also discovered something surprising about changes in the geosphere over time. In the middle grades, students explained how spatial patterns in the fossil record provide evidence that plates are moving (MS-ESS2-3). They can now revisit this understanding in light of evolution and populations and, as a result, better understand why the fossil evidence for plate tectonics is so compelling. Take, for example, fossils of a specific species of fossil fern, *Glossopteris*, that grew in narrow geographic regions on South America, Africa, India, and Australia. It is virtually impossible that the same species would evolve independently in different places at the same time. If it had been transferred to all these separate continents by some hypothetical wind current, then these new populations would have existed in isolation and would have been free to change and evolve providing a foundation for many speciation events (HS-LS4-5). While it did develop and change over the 40 million years or so that it dominated the vegetation of the southern continents, the changes in one location tracked the changes in others. This could only happen if they were part of a single, interconnected population. And that could only happen if the continents were once together and have since moved. Students learn about the mechanisms that drive plate motion in IS2 of the chemistry course.

The exact timing of these events can be tracked because of advances in radiometric dating techniques. Students learn about the details of these techniques in IS4 of the Physics of the Universe course and can address the basic principles here (HS-PS1-8). By determining the age of each rock layer, scientists can determine when the fossils contained within them were alive. The oldest seafloor in the Atlantic Ocean is 200 million years old, which indicates that the Americas began to be pulled away from Europe and Africa about 50 million years after the last Glossopteris went extinct. Students can evaluate the **evidence [SEP-7]** for other well-known species that spanned across continents around the same time (i.e., *Mesosaurus*, *Cynognathus*, *Lystrosaurus*, etc.) (HS-ESS1-5, though students are assessed on this performance expectation in the Chemistry in the Earth System course). None of them existed as the same species on two different continents after the continents broke apart, as demonstrated by the ages of the fossils. In fact, many of them went extinct around the same time at the end of the Permian Period, which is an interesting mass-extinction story in and of itself that could be discussed in IS6.

IS4

Living Earth Instructional Segment 4: Inheritance of Traits

Middle grade students are introduced to genes and the connection to genes and proteins, including what happens if there are mutations in gene sequences (MS-LS3-1) and the variation within individuals that are the result of the inheritance of genetic traits (MS-LS3-2). This instructional segment defines the mechanisms for inheritance that were introduced in IS3 and provides a motivation for understanding IS5 in which students learn how organisms use DNA to code for amino acids, the building blocks of proteins. While this instructional segment provides the big picture view of inheritance by DNA, IS5 goes into more detail about cell division and explains the mechanism of inheritance at the scale of the cell itself.

LIVING EARTH INSTRUCTIONAL SEGMENT 4: INHERITANCE OF TRAITS

Guiding Questions

- How are characteristics of one generation passed to the next?
- What allows traits to be transmitted from parents to offspring?
- How does variation affect a population under selective pressures?

Performance Expectations

Students who demonstrate understanding can do the following:

HS-LS3-1. Ask questions to clarify relationships about the role of DNA and chromosomes in coding the instructions for characteristic traits passed from parents to offspring. *[Assessment Boundary: Assessment does not include the phases of meiosis or the biochemical mechanism of specific steps in the process.]*

HS-LS3-2. Make and defend a claim based on evidence that inheritable genetic variations may result from: (1) new genetic combinations through meiosis, (2) viable errors occurring during replication, and/or (3) mutations caused by environmental factors. [Clarification Statement: Emphasis is on using data to support arguments for the way variation occurs.] *[Assessment Boundary: Assessment does not include the phases of meiosis or the biochemical mechanism of specific steps in the process.]*

HS-LS3-3. Apply concepts of statistics and probability to explain the variation and distribution of expressed traits in a population. [Clarification Statement: Emphasis is on the use of mathematics to describe the probability of traits as it relates to genetic and environmental factors in the expression of traits.] *[Assessment Boundary: Assessment does not include Hardy-Weinberg calculations.]*

HS-LS4-2. Construct an explanation based on evidence that the process of evolution primarily results from four factors: (1) the potential for a species to increase in number, (2) the heritable genetic variation of individuals in a species due to mutation and sexual reproduction, (3) competition for limited resources, and (4) the proliferation of those organisms that are better able to survive and reproduce in the environment. [Clarification Statement: Emphasis is on using evidence to explain the influence each of the four factors has on number of organisms, behaviors

LIVING EARTH INSTRUCTIONAL SEGMENT 4: INHERITANCE OF TRAITS

morphology, or physiology in terms of ability to compete for limited resources and subsequent survival of individuals and adaptation of species. Examples of evidence could include mathematical models such as simple distribution graphs and proportional reasoning.] *[Assessment Boundary: Assessment does not include other mechanisms of evolution, such as genetic drift, gene flow through migration, and co-evolution.]*

HS-LS4-3. Apply concepts of statistics and probability to support explanations that organisms with an advantageous heritable trait tend to increase in proportion to organisms lacking this trait. [Clarification Statement: Emphasis is on analyzing shifts in numerical distribution of traits and using these shifts as evidence to support explanations.] *[Assessment Boundary: Assessment is limited to basic statistical and graphical analysis. Assessment does not include allele frequency calculations.]*

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-4] Analyzing and Interpreting Data [SEP-6] Constructing Explanations (for science) and Designing Solutions (for engineering) [SEP-7] Engaging in Argument from Evidence	LS1.A: Structure and Function LS3.A: Inheritance of Traits LS3.B: Variation of Traits LS4.B: Natural Selection LS4.C: Adaptation	[CCC-1] Patterns [CCC-2] Cause and Effect: Mechanism and Explanation [CCC-3] Scale, Proportion, and Quantity

Highlighted California Environmental Principles and 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.

CA CCSS Math Connections: MP.2; MP.4

CA CCSS for ELA/Literacy Connections: RST.11–12.1, 9; WHST.9–12.1.a–e, 2.a–e, 7, 9

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

One way to help students meet HS-LS3-1 and better appreciate the nature of science is through a historical approach. Students obtain information about the study of DNA, learning about what scientists knew, what questions they asked, and how they designed investigations to answer those questions. Discussing the scientists themselves shows that science is a human endeavor. The historical approach also illustrates how ideas have unfolded over time, showing that scientific knowledge is open to revision in light of new evidence. See chapter 11 on instructional strategies for specific advice about teaching science through historical case studies.

At the turn of the twentieth century, Mendel's conclusions about inheritance were accepted, and it was understood that chromosomes were passed from generation to generation in all living organisms. It was also known that chromosomes were composed of DNA and proteins. However, in the early 1900s it was not clear to scientists how these chromosomes could provide the codes for all the phenotypes present in an organism. Were the proteins or the DNA most important? As scientists grappled with this, they began to ask more focused questions about what exactly was directing the translation of proteins. Frederick Griffith, one such scientist, was trying to find a cure for pneumonia and was using mouse models to address specific questions about how mice contracted pneumonia. He found that he could inject strains of bacteria into mice and transform strains of non-pathogenic bacteria into pathogen-causing bacteria. The full experiment might be demonstrated by a slide presentation showing the first part of Griffith's experiment on one slide while asking students to predict the outcomes. Then show the outcomes on the next slide, continuing this pattern with the next set of experiments as students predict the outcomes. Then see what comes next by switching to the next slide and building on that knowledge, continuing with the next set of experiments along with predictions. Students can deduce the control and variables Griffith used in his original work. The conclusion of his work was that some agent transformed the non-pathogen-causing strains into pathogen-causing strains of bacteria and the mice developed pneumonia.

MacLeod and McCarty attempted to answer that question. They discovered that DNA was the transforming agent, which they concluded after testing the individual components of the bacteria cell in a cell culture system. Scientists were not entirely convinced. Therefore, Alfred Hershey and Martha Chase radioactively labeled parts of viruses and provided even more evidence that the DNA was being transported into hosts' cells and transforming those host cells into virus-making machines. It was also around this time that Erwin Chargaff and his students who, while working on separating nucleotides in different organisms, noticed that adenine and thymine were always in the same amounts as were guanine and cytosine.

They also noticed that the total amount of adenine and thymine was not equal to the total amount of guanine and cytosine. A final piece of the puzzle was the X-ray photograph of DNA that Rosalind Franklin generated showing the regular pattern and the helix formation of the molecule. These experiments, along with other evidence gathered during this time, led to the building of the **model [SEP-2]** of DNA by Watson and Crick. (There is an excellent educational resource regarding the history of this scientific discovery through the UC Berkeley Museum of Paleontology, The structure of DNA: Cooperation and competition https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link10.)

Building physical **models [SEP-2]** can help explain data and observations (for Watson and Crick, it helped them merge together all that they had learned from others) and predict new possibilities (for Watson and Crick, it helped others think about how DNA replicates) but models also have limitations. For example, Watson and Crick's model could not show how the code determined amino acid order. Having students build this model can help them make the connections that Watson and Crick made with the data produced from theirs and others' experiments. Students can also begin to see what happens if a component of the model changes. What happens if you switch a thymine with an adenine? Students should see that having an A nucleotide across from an A nucleotide alters the structure, which can help them make predictions about the effect of mutations. Students can improve their ability to **obtain information [SEP-8]** from scientific journals by reading an annotated version of Watson and Crick's original paper. Even though it is only two pages long, it has profoundly influenced the direction of the science of genetics and molecular biology.

Much of the work done in the first half of the twentieth century looked at the effect mutations had on phenotypes. If a genetic disease resulted, it gave the geneticists evidence of the function of that gene, though they could not directly observe the genotype (see IS1). In the latter half of the twentieth century and into the twenty-first century, techniques and tools have improved so that scientists can actually test how specific changes in a gene sequence alter phenotypes. Technology has also enabled scientists to map out entire genomes of a large variety of organisms, and large online databases exist that students can browse freely (see National Center for Biotechnology Information https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link11).

Once scientists started mapping out entire genomes, they realized that the simple relationships between DNA sequences and phenotypes are more complicated than originally thought. Genomes contain far fewer gene sequences than scientists originally thought and many phenotypes are the results of more than one gene. Students can look at phenotype studies and **ask questions [SEP-1]** regarding what changes in DNA result in changes in phenotypes of humans (or other living organisms) and the effect of DNA changes on individuals. Students can go to National Center for Biotechnology Information and link to case studies done in humans by looking at the Online Mendelian Inheritance in Man (OMIM) link or they can expand the exercise and look at other animals or plants.

Students can investigate organ and tissue donation by **obtaining information [SEP-8]** about how doctors use genotypes to find successful matches for people who need new organs or tissue. The success of these transplants is much higher when the doctors can find a genotype match for certain traits (for additional information see organdonor.gov https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link12). Which genes are most important for identifying the right match? What other traits do those genes influence?

This instructional segment can now meld classic Mendelian genetics with the molecular genetics just discussed. Variation is the result of mutation and recombination events that happen at the genetic level. Students can apply a physical **model [SEP-2]** of chromosomes (such as clay or pipe cleaners) to visualize and provide **evidence [SEP-7]** about how variation happens. With this model, students can demonstrate how pairs of chromosomes physically exchange parts to create new combinations of sequences (one method of variation) and can show that the random line up of the chromosome pairs during meiosis results in different arrangements of chromosomes during sexual reproduction (another method of variation). Students can also use Punnett squares as a model that illustrates how variation can arise from the mating of two biological parents. **Analyzing [SEP-4]** the **quantity and proportion [CCC-3]** of possible outcomes helps explain the variation we see in individuals even between siblings who have the same biological parents.

Mutations in DNA can result in a change in genotype. Some mutations result in viable cells and can produce new genes that are then inherited by the next generation, others result in cell death, and still others in uncontrolled replication that leads to cancerous tumors. Sometimes, the traits caused by mutations result in a viable cell that somehow lacks certain functionality, and we refer to these mutations as genetic diseases. A single nucleotide change in the gene sequence for hemoglobin results in sickle cell anemia. A similar mutation in the gene that is used to form proteins that form a channel for movement of particles into and out of cells produces the condition known as cystic fibrosis (though it should be noted that there can be several single changes that result in the cystic fibrosis phenotype). Errors in copying or division of the X chromosome can lead to a disease resulting in Turner syndrome. Students should be able to use evidence from these genetic diseases to **construct an argument [SEP-7]** that variations are caused by genetic code that is inherited or altered either during DNA replication or by environmental factors (HS-LS3-2).

Students should also be able to relate this argument not only to genetic disease but also to any variation in traits.

Other mutations can actually make it harder for diseases to affect humans. Students could **obtain information [SEP-8]** about how a mutation in the gene that creates the protein CCR5 can delay or prevent acquired immune deficiency syndrome (AIDS) symptoms in people infected with the human immunodeficiency virus (HIV). They **develop a model [SEP-2]** of how viruses enter cells by matching protein receptors. Viruses like HIV, bubonic plague, and smallpox cannot enter the cell in people that lack the CCR5 protein receptor. Does this mutation provide clues to create an HIV treatment or vaccine? Students can also **analyze data [SEP-4]** from maps showing how common this mutation is in different parts of the world and **ask questions [SEP-1]** about why this mutation became so prevalent in northern European countries.

Once students understand how variation can occur, they can predict what combinations are possible in offspring. Punnett squares are a simple and common model used to predict traits, but they are cumbersome to use for predicting multiple traits. For example, predicting the outcome of a tri-hybrid cross requires a cumbersome eight by eight Punnett square. Instead, students can use statistical tools that include the product and sum rules of probabilities (CA CCSSM S-CP.7–8). Pedigrees are another model used to look at patterns of inheritance across generations. Students can evaluate possible genetic combinations and predict the chance of traits appearing in individual offspring. Students can use interactive computer simulations to create phenotypes of an organism by looking at combinations of genotypes and again predict what combinations are plausible. Students should be able to use information from genetics and their ability to calculate probabilities of different traits to explain the distribution of particular traits within a population (HS-LS3-3).

While genetics dictates many aspects of variation, environment also affects phenotype expression. Some environmental components can affect the phenotype without a change in genotype. In humans, nutrition is an environmental component that affects height or muscle formation. Just because an individual possesses the genotype to be tall or strong does not mean he or she will reach full genetic potential. Failure to meet genetic potential does not affect how genes are inherited, so malnourished parents can give birth to offspring that end up being much taller than their parents. Using statistics (**mathematical thinking [SEP-5]**), students can **analyze [SEP-4]** the frequency or distribution of traits observed in a population and compare it to the probability of certain traits occurring based on genetics alone (CA CCSSM S-CP.4). If students identify a mismatch, they should be able to construct an **argument [SEP-7]** that environmental factors have affected phenotypes.

Linking IS3 with this instructional segment will help students draw connections between how variation exists and how selection can act on the population. Natural selection acts on the phenotype of an individual, for example the size of a shell or beak. The selective pressure that favors one size over another will translate into a change in proportion of individuals with the favored size in the next generation—if the change is a result of inheritance. In other words, the individuals that have the favorable phenotype reproduce and pass on the favorable genetic code that generated that phenotype. The frequencies of favored traits are ultimately what change from generation to generation. Students can **model [SEP-2]** these changes using computer simulations of populations (see Howard Hughes Medical Institute "Color Variation Over Time in Rock Pocket Mouse Populations" at https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link13) and use **probabilities [SEP-5]** to determine whether or not there is evidence of changes in populations over time (see Howard Hughes Medical Institute "Stickleback Evolution Virtual Lab" at https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link14) (HS-LS4-3). Using these simulations as examples, students should be able to tie together their knowledge in the course to construct an explanation of how organisms evolve (HS-LS4-2). Their explanation should note how (1) organisms can reproduce to grow in numbers; (2) offspring of organisms are slightly different from their parents due to processes of mutations and sexual reproduction; (3) organisms compete for limited resources; and (4) organisms with traits that enable them to survive and obtain resources are most likely to reproduce and pass on their traits such that the population increases in the proportion of these successful traits.

IS5

Living Earth Instructional Segment 5: Structure, Function, and Growth (From Cells to Organisms)

Understanding the characteristics of life is a unifying theme of biology. Instructional segment 5 investigates the birth and operation of individual cells, something common to all life. After exploring life from the macroscopic level, students finally zoom down to the microscopic mechanisms with a focus on DNA's role in cellular operations.

LIVING EARTH INSTRUCTIONAL SEGMENT 5: STRUCTURE, FUNCTION, AND GROWTH (FROM CELLS TO ORGANISMS)

Guiding Questions

- What happens if a cell in our body dies?
- How does the structure of DNA affect how cells look and behave?
- How do systems work in a multi-celled organism (emergent properties) and what happens if there is a change in the system?
- How do organisms survive even when there are changes in their environment?

Performance Expectations

Students who demonstrate understanding can do the following:

HS-LS1-1. Construct an explanation based on evidence for how the structure of DNA determines the structure of proteins which carry out the essential functions of life through systems of specialized cells. *[Assessment Boundary: Assessment does not include identification of specific cell or tissue types, whole body systems, specific protein structures and functions, or the biochemistry of protein synthesis.]*

HS-LS1-2. Develop and use a model to illustrate the hierarchical organization of interacting systems that provide specific functions within multicellular organisms. [Clarification Statement: Emphasis is on functions at the organism system level such as nutrient uptake, water delivery, and organism movement in response to neural stimuli. An example of an interacting system could be an artery depending on the proper function of elastic tissue and smooth muscle to regulate and deliver the proper amount of blood within the circulatory system.] *[Assessment Boundary: Assessment does not include interactions and functions at the molecular or chemical reaction level.]*

HS-LS1-3. Plan and conduct an investigation to provide evidence that feedback mechanisms maintain homeostasis..[Clarification Statement: Examples of investigations could include heart rate response to exercise, stomate response to moisture and temperature, and root development in response to water levels.] *[Assessment Boundary: Assessment does not include the cellular processes involved in the feedback mechanism.]*

HS-LS1-4. Use a model to illustrate the role of cellular division (mitosis) and differentiation in producing and maintaining complex organisms. *[Assessment Boundary: Assessment does not include specific gene control mechanisms or rote memorization of the steps of mitosis.]*

LIVING EARTH INSTRUCTIONAL SEGMENT 5: STRUCTURE, FUNCTION, AND GROWTH (FROM CELLS TO ORGANISMS)

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-2] Developing and Using Models [SEP-3] Planning and Carrying Out Investigations [SEP-4] Analyzing and Interpreting Data [SEP-6] Constructing Explanations (for science) and Designing Solutions (for engineering)	LS1.A: Structure and Function LS1.B: Growth and Development of Organisms	[CCC-4] Systems and System Models [CCC-6] Structure and Function [CCC-7] Stability and Change

CA CCSS Math Connections: F-IF.7.a–e, F-BF.1a–c; MP.2, MP.4

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

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

Before starting IS5, teachers should assess what students know about the characteristics of life. For example, working in small groups, students can sort pictures of living and nonliving things into two categories and **support an argument [SEP-7]** for where they put each item. Objects can include plants, insects, mammals, electronics, plastic toys, as well as unusual examples and outliers such as a sponge, rock, lichen, tunicates, snakeskins, molds, and/or a skeleton. Students come to a consensus as to what goes in each category and why. After presenting their thinking to the entire class and listening to the thinking of their classmates, students re-sort the items. Groups discuss the similarities and differences between the living organisms. Instructional segment 5 also builds on other key ideas in life science that students engaged in during the middle grades, including: models of cells and how they interact in multicellular organisms (MS-LS1-1, MS-LS1-2 and MS-LS1-3). Formative assessments at the beginning of the course will help teachers determine what level of detail they will need to revisit to help students succeed.

Human skin cells have a lifespan of only a few weeks before they die, but we do not really notice because the new ones look identical to the old ones. We see evidence for this skin loss as we scrape off dead skin. How do cells do this? Students can watch cells divide during a video and observe that the two cells at the end look identical. What is the mechanism for making such exact copies?

In the middle grades, students developed a model of how genes stored information about how to make proteins (MS-LS3-2), but that model did not include DNA or how DNA is encoded in genes. Their model did include the fact that genes record information about traits or phenotypes. Now, students must **explain [SEP-6]** the mechanism by which the structure of DNA determines the structure of proteins and how this process determines the overall structure and function of the cell or organism.

As George Beadle (a biologist in the early twentieth century) said, “One ought to be able to discover what genes do by making them defective.” Students can start with the idea that DNA holds the information necessary for all phenotypes of the organism. Cells do not need all of this information at all times or in all cells (analogous to a library that holds lots of books arranged by subject, but only some of those books are checked out at certain times). But which parts of the DNA sequence contain the information for which phenotypes? Often, genes are mapped to phenotypes by looking at mutations. If a mutation alters the phenotype, then the section of DNA that mutated must be responsible for that phenotype.

Once students recognize a **cause and effect [CCC-2]** sequence between mutated genetic code in DNA and changes in phenotype, they are ready to examine the precise mechanism: How does a DNA sequence blueprint get translated into a phenotype? Students can use a codon table along with colored beads as a **physical model [SEP-2]** for protein synthesis. The lineup of the nucleotides on the DNA strand is the template for the order of the amino acids, which then determines which specific protein gets made based on its **structure [CCC-6]**. Students do not need to understand the details of the translation process, memorize a codon table, or map out metabolic pathways.

Historically, most of these connections were made by looking at mutants, and now students can observe this by looking at loss of function in strains of bacteria[3] or mutant strains of quick growing plants.[4] Mutation gene maps for model organisms are available and students can refer to these as they look at mutated phenotypes. Students can then gather **evidence [SEP-7]** to construct an **explanation [SEP-6]** for how a specific DNA sequence causes a specific loss of function, and can use this specific case to support the claim that there is a connection among DNA, the proteins cells produce, and the physical

3. It is possible to buy safe bacteria strains that are resistant to antibiotics from many biological supply companies and compare those strains to ones that are not resistant or to ones that grow in the presence of lactose and ones that cannot breakdown lactose and therefore change color.
4. A search on the Internet should provide links to companies that maintain normal and mutant seed stocks.

features of an organism (HS-LS1-1). Relating back to the discussion of mutations in IS4, students can **plan and carry out investigations [SEP-3]** to determine if mutants can grow in varying environments. Because students will need to refer back to their data to look at variations within populations and effects of environment on individuals within populations, teachers will need to introduce an organizational structure such as science note booking or student-created Web pages describing investigations with data stored in collaborative Web based spreadsheets.

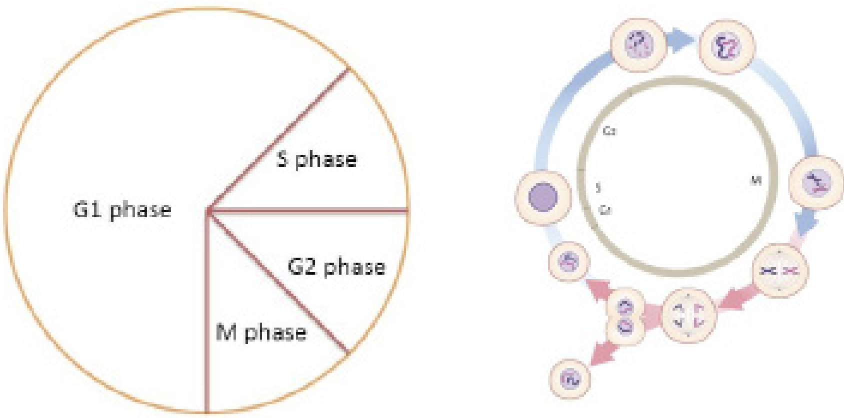
Mutations are technically tiny changes at the micro scale to DNA sequences, but how do these modifications affect the overall function of body systems at the **scale [CCC-3]** of an entire organism? While students constructed arguments that the body works as a set of interacting **systems [CCC-4]** in the middle grades (MS-LS1-3), now they are ready to understand some specific examples of interactions and the reason that these interactions are so important. Students can develop and use **models [SEP-2]** that show how a system works, then mutate part of it and observe the effects. A model that demonstrates how the movement of the diaphragm affects the pressure in the chest cavity allowing for our lungs to push out or take in air could either be pictorial (a labeled diagram showing interacting components of the respiratory system) or a physical model with tubes and plastic bags taped to a piece of cardboard to represent the lungs and diaphragm. If one lung is nonfunctional, what happens? Students should develop and use a model that explains not only how individual systems interact, but also how that interaction enables the functions of the entire organism (HS-LS1-2). While examples can come from any organism, this is a key opportunity within the CA NGSS to explore specific mechanisms within the human body.

One of the ways that cells work together in tissues, organs, and finally organ systems is to maintain **stability [CCC-7]** through homeostasis. Maintaining homeostasis means that despite changes in the environment an organism has the ability to maintain certain internal chemical and physical states. Students can measure their internal body temperature on a cold morning, a hot day, or after vigorous exercise. Even as the temperature outside spans as much as 40°C, a person’s internal temperature only varies by a few degrees. How does this happen and why does the body work so hard to maintain a constant temperature? The significance is in the functioning of proteins, especially when looking at enzymes, which must have stable environments to function correctly. Enzymes usually work in only a fairly narrow environmental range. For multicellular organisms, the first line of regulation is through their skin or outer layers (epithelium), which respond to stimuli in the environment. The brain then processes these stimuli and activates balancing feedback mechanisms to counteract the environmental change. When it is hot, mammals like humans sweat or pant, and when it is cold they shiver. Students can **plan and conduct investigations [SEP-3]** in which they change conditions for plants or animals and watch how they respond (HS-LS1-3). They can measure their own heart rate returning to normal after vigorous exercise, observe plants growing taller in the dark to reach new light sources, or observe the behavioral response of Planaria (flatworms) as the amount of light changes. Students do not need to explain the specific mechanisms that accomplish these changes (e.g., photosensitivity, hormone distribution, avoidance, etc.), but they should gather evidence that organisms respond to changes and use that evidence to construct a conceptual **model [SEP-2]** that can predict outcomes of future experiments that vary parameters from their initial trials.

One of the characteristics of life is the ability to grow (whether as a single cell or as a multi-cellular organism). In the 1860s, Rudolf Virchow proposed that new cells arose from pre-existing cells. As microscope technology advanced in the late 1800s, scientists were able to gather direct evidence supporting Virchow's claim. To go from a single cell (fertilized egg) to a multicellular organism, cells need to produce more cells. As unicellular organisms reproduce, they also make more cells. In both cases, information gets copied from the parent to the daughter cells. From IS4, students know that DNA records this information, but how do cells duplicate DNA?

Cells, just like organisms, have a life cycle referred to as the cell cycle (figure 7.9). The cell cycle is a conceptual model that describes the essential events in a cell's life. The assessment boundaries for HS-LS1-4 and HS-LS3-1 are clear that rote memorization of different stages of the cell cycle or mitosis is not the goal of the CA NGSS. One of the common consequences of differentiating between these stages is that students think of them as separate and independent events rather than a continuous evolution. Students should be able to describe the events and sequence of the cell-cycle model. They should be able to describe the stages that contribute to the overall goal of the process. In particular, students should ensure that their model includes the idea that organisms that reproduce sexually contain two sets of genetic material, one variation from each parent. Students should begin to ask questions about how these duplicate copies of DNA determine which traits offspring inherit from their parents (HS-LS3-1). Students must be able to use their model of the cell cycle to explain how organisms grow, how multi-cellular organisms copy the same genetic code but differentiate into different cell types, and how organisms replace dead cells with new ones (HS-LS1-4). Students can also apply their model to predict what happens when there are mistakes in this process. For example, what would happen if the stages of mitotic cell division do not occur in order (i.e., if cytokinesis occurs before mitosis)? Students can also use the model to explain cancer[5] and the effects of unchecked, out-of-control cell division on normal cell function.

Figure 7.9. Two Pictorial Models of the Stages of the Cell Cycle



Stages of the cell cycle. On the left, the size of the pie is proportional to the time spent in each phase. On the right, the icons visually depict what happens at each stage. *Source*: V. Vandergon; Genomics Education Programme 2014
Long description of Figure 7.9.

Cell division is the first part in the growth of an organism and as new cells are formed in multicellular organisms, they differentiate into specific cell types. These specific cell types then participate in the formation of a tissue, which then forms organs that are often parts of a physiological system in multicellular organisms (this links back to IS1). Many multicellular organisms stop growing once they reach adulthood, but mitosis does not stop. Some cells die off as they reach the end of their life cycle and these dead cells need to be replaced. This replacement of dead cells occurs through mitosis of the remaining living cells. Extensions of this instructional segment might include discussions of stem cells that have not yet differentiated and have the ability to become a variety of types of cells, leading to new tissue and organ formation. Stem cells used in organ transplant provide a way for scientists to help decrease rejection of transplanted organs by the recipient of the donated organ. Stem cells can be used to generate signals for the recipient's body so that their immune system thinks that the organ belongs there.

5. Resources are available to look at cancer rates and types. See Cancer Research Center http://www.cde.ca.gov/ci/sc/cf/ch7.asp#link166 which has short YouTube videos as well as the latest on cancer research. Make sure to use reputable government supported research sites.

This instructional segment culminates with students researching and **constructing an explanation [SEP-6]** about how different diseases cause a cascade effect in the interdependent **systems [CCC-4]** of the human body (HS-LS1-2). Amyotrophic Lateral Sclerosis (ALS, also known as Lou Gehrig's disease) is a good example of a disease that results in multiple effects on the body systems, but there are many such diseases in humans (e.g., cystic fibrosis, muscular dystrophy). The cause of ALS is still uncertain and only about 5–10 percent of cases can be traced to genetic inheritance of a mutated gene. Most of the time there is a random event that causes a neurodegenerative progression of the nerve cells in the brain and the spinal cord so that the muscles in the human body do not receive messages and therefore begin to atrophy from disuse. As the muscles atrophy, other systems in the body are affected. For example, muscles in the respiratory system stop working and the individual with ALS has trouble breathing. Students should also obtain information about treatments and solutions that modern medicine has found for these diseases. In diseases where organs fail, teachers can highlight the importance of organ transplants and how donations of working organs and tissues from others can save lives.

Engineering Connection: Organ Donation

Students can learn about the role of engineering to meet critical medical needs to solve another problem in organ donation: matching suitable donors with patients. In addition to striking examples of engineering like magnetic resonance imaging (MRI) and robotic surgery, some engineers also develop important processes such as matching donors and patients by breaking down the problem into smaller, more manageable problems. Students can consider the different aspects of the problem of donor matching (e.g., awareness about the process by potential donors, rapid and reliable genetic testing, etc.) and brainstorm and evaluate possible solutions to them.

High School Three-Course Model Living Earth Snapshot 7.4: How Did We Eradicate Diseases in the US?

Anchoring phenomenon: Tuberculosis used to kill millions of people but it is no longer common.

Ms. H. introduced a historical case study about the different factors that go into eradicating diseases. Even though students may not remember it, most children admitted to school in California are tested for TB. Despite this common practice, it's likely that many students have never met anyone who had TB and may not even know that it stands for tuberculosis. So why all the fuss with TB tests? Ms. H told students that if she were teaching 200 years ago, the class would have lived in fear of this disease. During the nineteenth century, TB caused as many as 20 percent of the deaths in some years. Today, fewer than 250 people in all of California die of the disease in an average year (California Department of Public Health 2015). How did society accomplish this change?

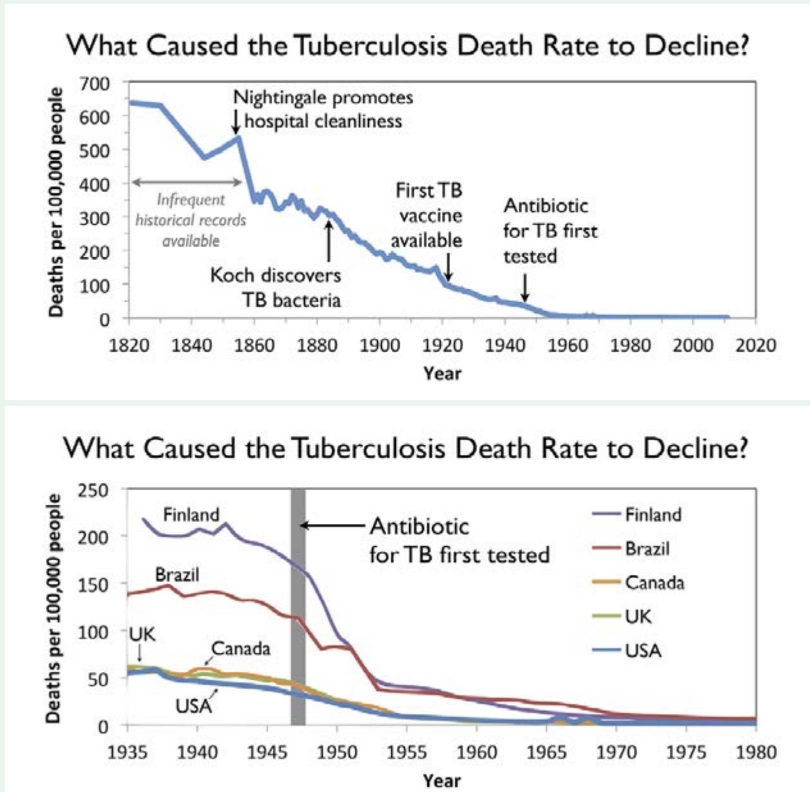
Ms. H divided the class into two groups that **obtain and evaluate information [SEP-8]** from different articles that introduce historical case studies of two major scientific innovations: (1) the origin of modern germ theory, including the discovery of tuberculosis bacteria by R. Koch in 1882; and (2) the application of science practices to randomized controlled drug trials, including the very first large-scale trial which tested an antibiotic to combat tuberculosis. Each group answered focus questions about the nature of science and core ideas about disease transmission. What effect did each of these innovations have on tuberculosis death rates?

Investigative phenomenon: The death rate from tuberculosis dropped several times during the last 200 years.

Ms. H provided each group with a graph (figure 7.10) showing how death rates changed around the time of the events described in their article. Students **analyzed the graphs [SEP-4]**, identifying **trends [CCC-1]** and looking for evidence of possible **cause and effect relationships [CCC-2]** between events labeled on the graph and changes in the death rate. Students reorganized in jigsaw style—two students from the group that discussed Koch's investigation **communicated [SEP-8]** their findings to two students that discussed the antibiotic trial (and then they switched). Students had to present an **argument [SEP-7]** about whether or not their group's innovation led to a significant decline in TB-related death rates (using their group's graph as evidence). Students realized that there was evidence that both sets of innovations may have helped, but also that rapid declines in death rates seem to happen even before some of the major events.

High School Three-Course Model Living Earth Snapshot 7.4: How Did We Eradicate Diseases in the US?

Figure 7.10: Two Graphs of the Decline of Tuberculosis



Charts by M. d'Alessio with data from Antunes and Waldman 1999; United States Census Bureau 1975; Official Statistics of Finland 2010; Public Health England n.d.; Gallant, Ogunnaike-Cooke, and McGuire 2014; Wikipedia 2016
Long description of Figure 7.10.

Ms. H wanted her high school students to move beyond the simple understanding of linear **cause and effect relationships [CCC-2]** from elementary school. According to the progression of CCCs in appendix 1 of this framework, high school students should recognize that changes in systems may have various causes that may not have equal effects. This is especially true when it comes to the health revolution that eradicated so many diseases like TB (Aiello, Larson, and Sedlak 2007). Innovations in medicine (drawn directly from scientific discoveries) influenced cultural norms for sanitation (such as hand washing) and led to changes in public policy and land use. These innovations occurred within the context of new technologies such as water filtration and sewage treatment that enhanced the standard of living in the United States and other western countries. Students watched a short video highlighting some of these key advances that dramatically

High School Three-Course Model Living Earth Snapshot 7.4: How Did We Eradicate Diseases in the US?

increased life expectancy. Monitoring efforts, including the TB tests taken by most California students, are part of this process. No individual factor is the singular cause of this health revolution. Ms. H led a whole-class discussion during which they generated a collaborative concept map representing society as a **system [CCC-4]** in which changes to different components result in the revolutionary overall system behavior where infectious disease no longer dominates our lives and deaths.

IS6 Living Earth Instructional Segment 6: Ecosystem Stability and the Response to Climate Change

In this instructional segment students will study the effects of natural and human-induced changes on ecosystems and the populations within them. In the middle grades, students learned that any change, either physical or biological, to an ecosystem can lead to a change in populations living in that ecosystem (MS-LS2-4). They now build on that knowledge to explore more complicated changes, many relating to shifts in global climate.

LIVING EARTH INSTRUCTIONAL SEGMENT 6: ECOSYSTEM STABILITY AND THE RESPONSE TO CLIMATE CHANGE

Guiding Questions

- What effects changes in ecosystems that ultimately effect populations?
- What are the changes that are happening in the climate and what effects are those having on life?
- How are human activities impacting Earth's systems and how does that affect life on Earth?
- What can humans do to mitigate their negative impact on the environment?

Performance Expectations

Students who demonstrate understanding can do the following:

HS-LS2-6. Evaluate the claims, evidence, and reasoning that the complex interactions in ecosystems maintain relatively consistent numbers and types of organisms in stable conditions, but changing conditions may result in a new ecosystem. [Clarification Statement: Examples of changes in ecosystem conditions could include modest biological or physical changes, such as moderate hunting or a seasonal flood; and extreme changes, such as volcanic eruption or sea level rise.]

HS-LS2-7. Design, evaluate, and refine a solution for reducing the impacts of human activities on the environment and biodiversity.* [Clarification Statement: Examples of human activities can include urbanization, building dams, and dissemination of invasive species.]

LIVING EARTH INSTRUCTIONAL SEGMENT 6: ECOSYSTEM STABILITY AND THE RESPONSE TO CLIMATE CHANGE

HS-LS4-5. Evaluate the evidence supporting claims that changes in environmental conditions may result in: (1) increases in the number of individuals of some species, (2) the emergence of new species over time, and (3) the extinction of other species. [Clarification Statement: Emphasis is on determining cause and effect relationships for how changes to the environment such as deforestation, fishing, application of fertilizers, drought, flood, and the rate of change of the environment affect distribution or disappearance of traits in species.]

HS-LS4-6. Create or revise a simulation to test a solution to mitigate adverse impacts of human activity on biodiversity.* [Clarification Statement: Emphasis is on designing solutions for a proposed problem related to threatened or endangered species, or to genetic variation of organisms for multiple species.]

HS-ESS3-5. Analyze geoscience data and the results from global climate models to make an evidence-based forecast of the current rate of global or regional climate change and associated future impacts to Earth systems. [Clarification Statement: Examples of evidence, for both data and climate model outputs, are for climate changes (such as precipitation and temperature) and their associated impacts (such as on sea level, glacial ice volumes, or atmosphere and ocean composition).] *[Assessment Boundary: Assessment is limited to one example of a climate change and its associated impacts.]*

HS-ESS3-6. Use a computational representation to illustrate the relationships among Earth systems and how those relationships are being modified due to human activity. [Clarification Statement: Examples of Earth systems to be considered are the hydrosphere, atmosphere, cryosphere, geosphere, and/or biosphere. An example of the far-reaching impacts from a human activity is how an increase in atmospheric carbon dioxide results in an increase in photosynthetic biomass on land and an increase in ocean acidification, with resulting impacts on sea organism health and marine populations.] *[Assessment Boundary: Assessment does not include running computational representations but is limited to using the published results of scientific computational models.]*

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.

LIVING EARTH INSTRUCTIONAL SEGMENT 6:
ECOSYSTEM STABILITY AND THE RESPONSE TO CLIMATE CHANGE

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-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	LS2.C: Ecosystem Dynamics, Functioning, and Resilience LS4.C: Adaptation LS4.D: Biodiversity and Humans ESS2.D: Weather and Climate ESS3.D: Global Climate Change ETS1.A: Defining and Delimiting Engineering Problems ETS1.B: Developing Possible Solutions ETS1.C: Optimizing the Design Solution	[CCC-2] Cause and Effect: Mechanism and Explanation [CCC-4] Systems and System Models [CCC-7] Stability and Change Influence of Science, Engineering, and Technology on Society and the Natural World

Highlighted California Environmental Principles and 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; S-ID.1; S-IC.1, 6; MP.2

CA CCSS for ELA/Literacy Connections: RST.9–10.8; RST.11–12.1, 2, 7, 8; WHST.9–12.2.a–e, 7, 8, 9

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

In high school, students confront complicated chains of **cause and effect [CCC-2]** that can work within ecosystems. For example, many human-induced **changes [CCC-7]** in ecosystems have unintended consequences, meaning humans did something to an ecosystem for one reason without realizing that there would be changes to other components of the ecosystem, or they had to balance other priorities (EP&C V). In other cases, natural changes to the physical system can cause cascading impacts on the living populations within ecosystems. A flood might drown many of the animals that live within the floodplain area (a density-independent factor), but this may in turn cause other animals to migrate and compete for resources or territory (density-dependent factors). This pressure could cause a shift in the ecosystem as a whole; if the population ends up depleting or eliminating resources, then the ecosystem may not be able to recover to its original state. Students can observe these changes through data-rich case studies and through computer simulations. Once they have developed conceptual models of ecosystem changes, they should be able to **evaluate different claims [SEP-7]** about the impacts of a new, hypothetical change (HS-LS2-6).

Populations with variation in their gene pool are more often able to withstand selective pressures as long as some of the individuals' phenotypes are advantageous for the population given the environment. Often, there are many variations in a population that do not confer particular advantages at the moment; however if there is a change in the environment, these phenotypes may then have an advantage. Those individuals that survive and produce living offspring are said to have the advantageous phenotype. The advantageous phenotype that survived while others disappeared is called an *adaptation*.

The majority of this instructional segment centers on how populations respond to the varied stresses due to climate change. What sort of changes will occur in ecosystems? What sort of variations will be beneficial to populations?

Climate Change Background

Many of the changes facing ecosystems today are related to changes in abiotic factors caused by climate change. Before understanding the effects of climate change, it is important to first examine the causes. While the details of global climate change are complex and technical, the underlying science is fundamentally simple and has been known for a long time. The main ideas relate to

- the flows of energy into, within, and out of the Earth system;
- Earth's cycles of matter, especially the carbon cycle;
- the effects of human activities, especially the combustion of fossil fuels.

Students can make a conceptual model of Earth's energy budget using an analogy of the line for a ride at an amusement park. The constant stream of eager visitors arriving at the end of the line represents solar radiation. As visitors get on the ride at the front of the line, they act like energy radiating out into space. Earth's global average temperature measures the amount of heat stored internally in Earth's system and so it is like the number of people waiting in line at any given time. The line will remain the same length if people get on the ride as quickly as new people arrive at the end of the line. Earth's temperature will remain **stable [CCC-7]** as long as the energy input and output remain unchanged.

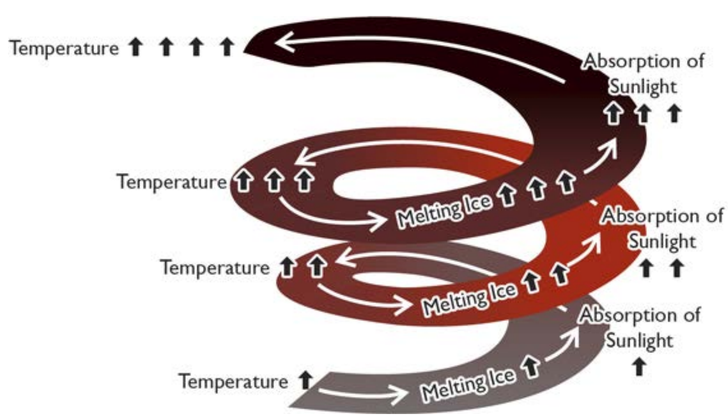
Earth's energy input comes almost entirely from the Sun. While a small amount of radioactive decay within Earth's interior generates heat, the flow of solar energy to Earth's surface is about 4,000 times greater than the flow of energy from Earth's interior to its surface. Relatively small changes in the solar input can result in an Ice Age or the melting of all of Earth's ice, much like the sudden arrival of a large group at an amusement ride can cause the line to quickly grow longer. The line will stabilize at this new length (without continuing to grow) as long as the influx of people returns back to its original rate. Planets can do the same thing, maintaining their temperature at a new value after a temporary disturbance.

Most of the sunlight that reaches Earth is absorbed and is transformed to thermal energy. If there were no atmosphere to hold that energy, it would radiate right back into space as infrared radiation (like an unpopular amusement park ride where people get on as soon as they arrive because there is no line). Gases in the atmosphere, such as CO_2, absorb infrared energy heading into space and cause it to remain within the Earth's system for a longer period of time. Because these gases have the same effect as a greenhouse, with heat trapped inside the system, gases like CO_2 are referred to as *greenhouse gases*. Calculations by scientists show that if Earth had no greenhouse gases, its surface temperature would be near 0°F (or -18°C) instead of its current value of a much warmer 59°F (15°C). The energy coming into the Earth is still balanced almost exactly by what is leaving the planet, but there is enough heat trapped in the system to allow life to thrive (like the amusement park ride whose line is always the same length).

By increasing the amount of greenhouse gases in the atmosphere, human activities are increasing the greenhouse effect and warming Earth's climate. In a given year, less energy leaves Earth than arrives. It is like one of the seatbelts breaking on the amusement park ride and fewer people are able to get on the ride. All of a sudden, the line gets longer and longer as new people arrive because people are not able to leave the line as quickly at the front. At the amusement park, this might lead to impatient children. On Earth, the imbalance in energy flows leads to an overall rise in average temperature.

Amusement parks and planets are **systems [CCC-4]** with complicated inner workings. When lines for one ride at an amusement park get too long, visitors inside the park may respond by going to another ride or park operators may add additional workers or cars to help move people through more quickly. Similar changes happen in Earth's web of systems. While the greenhouse effect seems like a simple **cause and effect [CCC-2]** relationship viewed from outside the system, interactions *within* the system can often give rise to more complicated chains of cause and effect referred to as *feedbacks*. Climate scientists are particularly concerned about feedback effects that could increase the amount and rate of global climate change. One example is that global warming is clearly reducing the amount of ice on our planet. Glaciers around the world are shrinking in size and even disappearing. The amount of ice covering the ocean in summer and fall is also shrinking. As the ice melts, the surface beneath it is darker in color and absorbs more incoming sunlight. More absorption causes more heating, and this heating causes even more absorption of sunlight (figure 7.11). This kind of feedback loop amplifies or reinforces the change, and the distinction between cause and effect begins to blur as each effect causes more change. The clarification statements in the CA NGSS and many scientists use the term *positive feedback*, but because many forms of feedback have very negative outcomes, the term positive feedback often leads to confusion. This term could be replaced by a more descriptive term, such as *reinforcing feedback*.

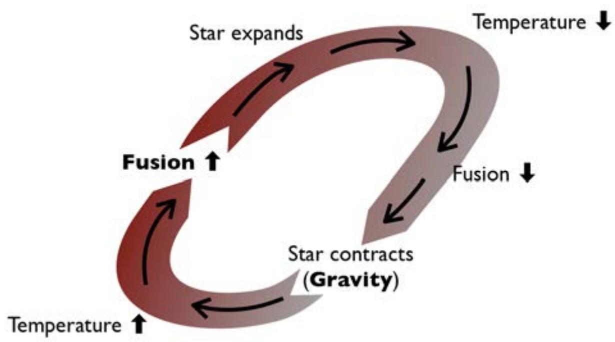
Figure 7.11. A Reinforcing Feedback in Earth's Climate



A reinforcing feedback in Earth's climate system. As the planet warms, more ice will melt, which will expose darker ground surfaces that absorb more sunlight, which will in turn make temperatures rise even more. Diagram by M. d'Alessio and A. Sussman
Long description of Figure 7.11.

A counterbalancing feedback loop reduces the amount of change (figure 7.12). For example, warmer temperatures cause more water to evaporate which enables more clouds to form. Clouds reflect sunlight back into space; therefore, more clouds cause more incoming solar energy to be reflected before the planet can absorb it. This causes decreasing global temperatures. More warming could cause more cloud formation and reflection, which would then lead to less warming again.[6] These changes are opposite and can balance each other out.

Figure 7.12. A Counterbalancing Feedback in Earth's Climate System



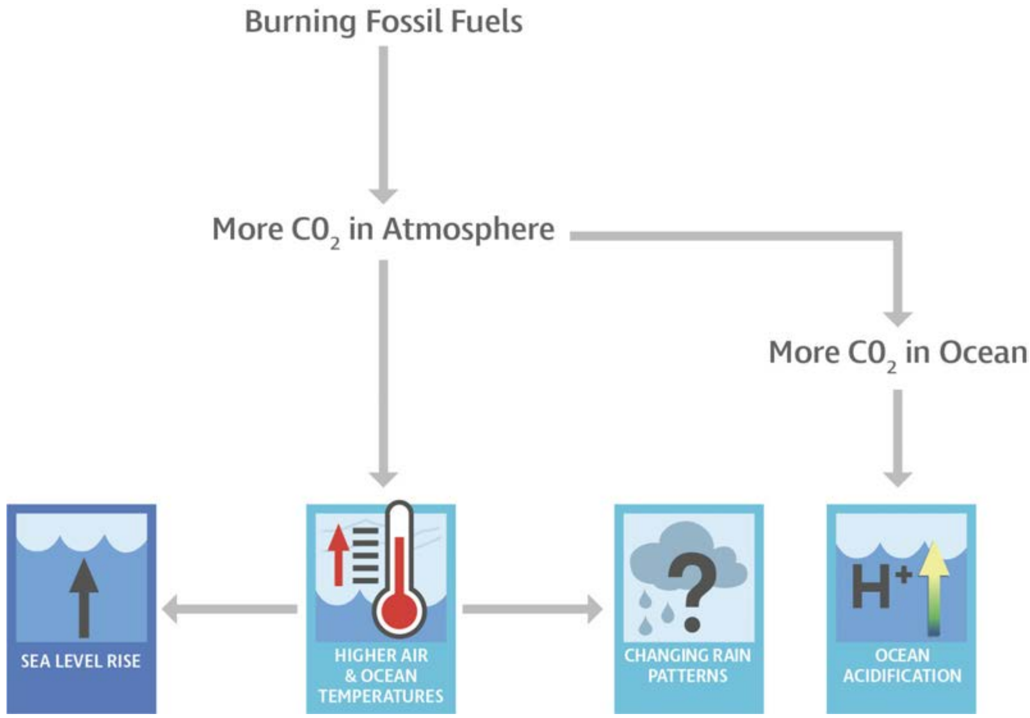
Temperature changes cause changes to the number of clouds because of evaporation. Clouds, in turn, reflect light. Diagram by M. d'Alessio and A. Sussman
Long description of Figure 7.12.

Predicting Climate Change Impacts on Ecosystems

Many of the feedbacks in climate change involve ecosystems as part of the chain of events, resulting in drastic changes to the abiotic conditions. How much will ecosystems change? Global climate models allow scientists and students to see how the climate is expected to change as greenhouse gases trap more energy in the atmosphere. Because of the linkages between different components of Earth's **systems [CCC-4]**, the impacts extend to all of Earth's systems (figure 7.13 shows an example of a few of these linkages).

6. Even though this example describes a counterbalancing feedback involving clouds, clouds are also involved in a reinforcing feedback where they trap more heat, causing more evaporation, and more clouds that trap more heat. Both of these mechanisms occur on Earth. The question researchers are currently trying to answer is, "Which feedback loop is more powerful, reinforcing or counterbalancing?" **Cause and effect [CCC-2]** gets very complicated in the Earth system

Figure 7.13. Human Impacts on the Earth System Related to Climate Change



One example of how humans affect the climate, which impacts all parts of Earth's systems. Illustration by Dr. Art Sussman, WestEd, and Lisa Rosenthal, WGBH n.d.
Long description of Figure 7.13.

Models [SEP-2] can help scientists predict how a climate change can effect populations within an ecosystem, especially over time. Students can employ simple computational simulations to explore real world population impacts (HS-ESS3-6, HS-LS2-1). For example, sea stars in California's coastal tide pools have seen a recent spike in an illness called *wasting disease* that causes death in a matter of a few days. The problem is dramatic and students can even report observations of afflicted organisms to a long-term monitoring project online (see UC Santa Cruz, "Sea Star Wasting Syndrome" at https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link15). The cause is currently unknown, but one hypothesis is that a species of *Vibrio* bacteria may infect them. Bacteria thrive in warmer temperatures, so seasonal cooling is an important moderator of bacteria populations. Climate forecasts predict that winter temperatures will increase. Will this cause a *Vibrio* bacteria population explosion? Students can design a computer **model [SEP-2]** by looking up laboratory experiments on bacteria growth (freely available online) and have their model mimic bacteria growth in ocean water temperatures that match climate forecasts. Students can use the model to assess the impact on coastal tide pool populations that are infected by the bacteria (HS-LS2-6). Other similar problems can be modeled such as the rise in malaria as mosquitoes extend their range to higher elevations or changing growing conditions suitable for rice, wheat, and other food staples (due to changes in rainfall and temperature). The chemistry section of the High School Four-Course Model (chapter 8) describes a similar simulation exploring the impact of ocean acidification on plankton species. Fully meeting HS-ESS3-6 requires that students not only obtain information about the problem, but also use simulations of the interaction of different Earth systems (including the biosphere) to demonstrate the specific impacts of human activities. They can also use these computer simulations to evaluate potential solutions to these problems (HS-ETS1-4).

High School Three-Course Model Living Earth Snapshot 7.5: Food Diaries

Everyday phenomenon: Different people eat different foods each day.

Ms. M partnered with the health teacher at her school to have students record everything they ate and drank for three days. Students entered their diets into an online tool (USDA "Supertracker" at https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link16) that reported their intake of different nutrients and they examined their individual diets in the health class. In Ms. M's class, they used a different online tool to calculate the total carbon emissions from the production and transport of their food (CleanMetrics "Food Carbon Emissions Calculator" at https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link17). Students then entered all their data into a single online spreadsheet to compare each student's carbon footprint from food and intake of nutrients like fat, sodium, carbohydrates, and fiber (though Ms. M hid the column with student names). The class **analyzed the data [SEP-4]** and noticed several **patterns [CCC-1]**, such as students that ate more vegetables and less meat had lower carbon footprints. Ms. M. asked students to create an infographic illustrating the foods that are both healthy for people and healthy for the climate. They prepared a presentation **communicating [SEP-8]** their findings to the people that ran the school lunch program and posted their infographic in the cafeteria.

Engineering Connection: Conservation Biology

When conservation biologists develop strategies to save endangered and threatened species, they are engaging in one form of engineering design. Conservation biologists help save these species by (1) supporting the use of wildlife corridors, which link large areas of land to other large areas so animals can migrate safely; (2) developing breeding programs for protecting endangered species; (3) identifying specific hotspots of species-rich regions worthy of extra protection and determining plans that provide sufficient protection; (4) arguing for the maintenance of larger environment regions instead of habitat fragmentation; (5) observing genetic diversity in small populations; and (6) monitoring the effects of climate change on all ecosystems.

As climate shifts, some organisms might need to migrate to new locations during part or all of the year, but their pathways could be interrupted by a freeway, fence, or other obstacle. Teachers can present students with a challenge to evaluate several possible plans for a wildlife corridor beneath a freeway and the possible expansion of a protected open space, which would allow them to use engineering design practices to **solve a real-world problem [SEP-6]** in an ecosystem using the tools and strategies of conservation biology. As they **obtain more information [SEP-8]**, including the needs of people as well as plants and other animals, they refine their solution (EP&C V; HS-LS2-7).

High School Three-Course Model Living Earth Snapshot 7.6: Shrinking Pika Habitat

Anchoring phenomenon: Pikas live only at high elevations (and are adorable).

Mr. R started class off by showing a slideshow of adorable creatures called pikas that live in the eastern Sierra Nevada and other mountains around the world. Pikas' bodies are so well adapted to the colder climates of higher elevations that they can overheat in warm temperatures and die in temperatures as low as 80°F after a few hours. While other animals can relocate to higher locations in the mountains, pikas already live at the highest elevations and they could not survive the migration down from one high peak to another. The pikas serve a unique role in the high-altitude ecosystems where they live: they build piles of grass that help fertilize the soil and fix nitrogen and they are also a food source for larger predators within the sparsely populated high altitude regions. Without an understanding of the interwoven nature of life with the Earth's systems it is hard to justify what all the fuss is about for a single small organism.

High School Three-Course Model Living Earth Snapshot 7.6: Shrinking Pika Habitat

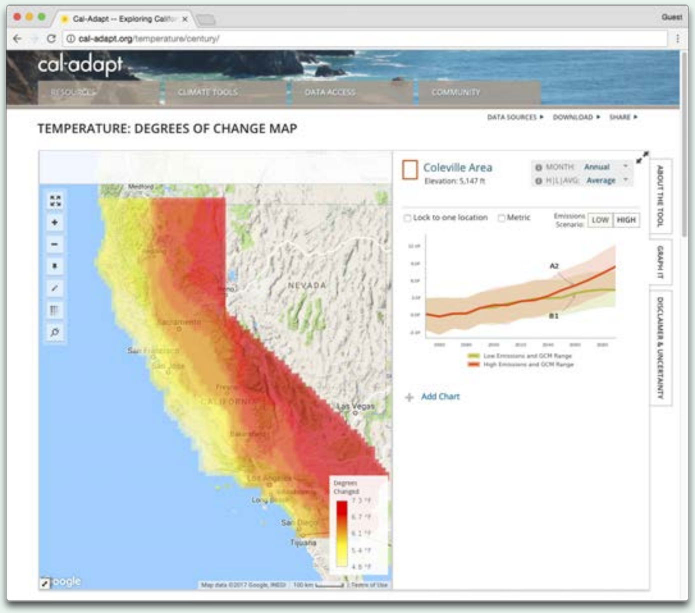
Investigative phenomenon: Global warming will increase the temperatures at high elevations.

Mr. R told students that they would be making a kinesthetic **model [SEP-2]**, a model using their bodies, demonstrating the effects of climate change on pikas. Mr. R scattered a supply of wooden sticks on the soccer field before class to represent plants that the pikas would collect for their winter food supplies. He placed orange cones in a triangle shape with the peak of the triangle representing the peak of a mountain and the long side representing the lowest point on the mountain where pikas could survive. If they strayed below that line, they would overheat and could die. Each person played the part of a pika and had to collect sticks and bring them back to their burrow, one at a time (pikas cannot carry much). By the time winter came, they had to have collected 10 sticks. Students ran around frantically collecting sticks until Mr. R announced the coming of winter. He then shrank the area enclosed by the cones announcing that global warming had reduced the area. Students found that there were insufficient sticks for all of them to survive. He repeated the process a third time, keeping the size of the mountain constant but giving students more time to search for sticks, representing a longer summer. More of the pikas survive.

Students returned to the computer lab and Mr. R showed them a computer simulation of the exact situation that they encountered in the kinesthetic activity (HS-ETS1-4). He emphasized that both were examples of **models [SEP-2]**. Students could adjust the temperature and watch how the size of the pika habitat shrank and grew. The simulation was sophisticated and students could adjust the temperature month-by-month. They could explore the **effect [CCC-2]** of longer summers and see how that affected vegetation growth (so that pikas had more food available) or warmer winters, in which pikas needed less food to survive. Students then visited the California Energy Commissions, Cal-Adapt Web site (https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link18) and found specific temperature forecasts for the habitat of the pika in the Eastern Sierra (HS-ESS3-5). They saw that the average temperature in August was expected to rise by 10°F between 2000 and 2100 under one scenario, but only 3°F if humans emit less carbon dioxide from their use of fossil fuels (figure 7.14). Students quickly entered the temperature changes into their simulator to explore the impact of the predictions on the pika.

High School Three-Course Model Living Earth Snapshot 7.6: Shrinking Pika Habitat

Figure 7.14: Temperature Forecast for Habitat of the Pika



Source: California Energy Commission 2015
Long description of Figure 7.14.

Investigative phenomenon: What can people do to protect pikas and the rest of their ecosystem?

Students recognize from the simulator that pikas do much better under the low-emission scenario than the high-emissions scenario (HS-ESS3-6). Students can analyze the problem and identify protection of the entire ecosystem as part of their criteria for their solution (HS-ETS1-1). As the environment warms what can humans do to help the pikas and their ecosystem? Students need to break the problem down into smaller, more manageable problems (HS-ETS1-2), identifying criteria and constraints for successful solutions, and then comparing alternative solutions against the criteria and constraints to determine which is most likely be successful. They then modify the computer simulation they used earlier to include the effects of their solution (HS-LS4-6). How can they parameterize their solution in computer code? How much does it benefit the pikas?

Source: Inspired by Parks Climate Challenge 2009

Many solutions to these problems may focus on addressing the causes of climate change, such as the global reliance on fossil fuels for energy generation. Both the chemistry and physics sections of the High School Four-Course Model (chapter 8) consider these questions and links should be made to those courses. In the past, comparative costs of different energy sources have been based on dollar cost to the consumer, but new studies have taken into account a wider variety of costs including degradation of natural ecosystems, health impacts, and water and air pollution. This course on the living Earth is uniquely positioned to emphasize the importance of these measures when evaluating competing design solutions in all disciplines (HS-ETS1-3). Content from the EEI curriculum helps support many of these concepts, including the lessons on biodiversity: *The Keystone to Life on Earth* and the *Greenhouse Effect on Natural Systems.*

Teachers of the high school biology course may want to culminate with a project in which students apply what they have learned about how organisms maintain life. For example, students could compare and contrast how a few different organisms maintain life (e.g. human, redwood tree, and *E. coli*). The students should use **evidence [SEP-7]** to support their **explanations [SEP-6]** and they should effectively **communicate [SEP-8]** their **models [SEP-2]**.

LIVING EARTH VIGNETTE 7.1: ANALYZING THE PAST, PRESENT, AND FUTURE OF MARINE MAMMAL EVOLUTION

Performance Expectations

Students who demonstrate understanding can do the following:

HS-LS2-2. Use mathematical representations to support and revise explanations based on evidence about factors affecting biodiversity and populations in ecosystems of different scales. [Clarification Statement: Examples of mathematical representations include finding the average, determining trends, and using graphical comparisons of multiple sets of data.] *[Assessment Boundary: Assessment is limited to provided data.]*

HS-LS2-6. Evaluate the claims, evidence, and reasoning that the complex interactions in ecosystems maintain relatively consistent numbers and types of organisms in stable conditions, but changing conditions may result in a new ecosystem. [Clarification Statement: Examples of changes in ecosystem conditions could include modest biological or physical changes, such as moderate hunting or a seasonal flood; and extreme changes, such as volcanic eruption or sea level rise.]

HS-LS4-1. Communicate scientific information that common ancestry and biological evolution are supported by multiple lines of empirical evidence. [Clarification Statement: Emphasis is on a conceptual understanding of the role each line of evidence has relating to common ancestry and biological evolution. Examples of evidence could include similarities in DNA sequences, anatomical structures, and order of appearance of structures in embryological development.]

HS-LS4-5. Evaluate the evidence supporting claims that changes in environmental conditions may result in: (1) increases in the number of individuals of some species, (2) the emergence of new species over time, and (3) the extinction of other species. [Clarification Statement: Emphasis is on determining cause and effect relationships for how changes to the environment such as deforestation, fishing, application of fertilizers, drought, flood, and the rate of change of the environment affect distribution or disappearance of traits in species.]

HS-ESS2-7. Construct an argument based on evidence about the simultaneous coevolution of Earth's systems and life on Earth. [Clarification Statement: Emphasis is on the dynamic causes, effects, and feedbacks between the biosphere and Earth's other systems, whereby geoscience factors control the evolution of life, which in turn continuously alters Earth's surface. Examples include how photosynthetic life altered the atmosphere through the production of oxygen, which in turn increased weathering rates and allowed for the evolution of animal life; how microbial life on land increased the formation of soil, which in turn allowed for the evolution of land plants; or how the evolution of corals created reefs that altered patterns of erosion and deposition along coastlines and provided habitats for the evolution of new life forms.] *[Assessment Boundary: Assessment does not include a comprehensive understanding of the mechanisms of how the biosphere interacts with all of Earth's other systems.]*

HS-ESS3-4. Evaluate or refine a technological solution that reduces impacts of human activities on natural systems.* [Clarification Statement: Examples of data on the impacts of human activities could include the quantities and types of pollutants released, changes to biomass and species diversity, or areal changes in land surface use (such as for urban development, agriculture and livestock, or surface mining). Examples for limiting future impacts could range

LIVING EARTH VIGNETTE 7.1: ANALYZING THE PAST, PRESENT, AND FUTURE OF MARINE MAMMAL EVOLUTION

from local efforts (such as reducing, reusing, and recycling resources) to large-scale geoengineering design solutions (such as altering global temperatures by making large changes to the atmosphere or ocean).]

HS-ESS3-6. Use a computational representation to illustrate the relationships among Earth systems and how those relationships are being modified due to human activity.* [Clarification Statement: Examples of Earth systems to be considered are the hydrosphere, atmosphere, cryosphere, geosphere, and/or biosphere. An example of the far-reaching impacts from a human activity is how an increase in atmospheric carbon dioxide results in an increase in photosynthetic biomass on land and an increase in ocean acidification, with resulting impacts on sea organism health and marine populations.] *[Assessment Boundary: Assessment does not include running computational representations but is limited to using the published results of scientific computational models.]*

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.

*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*:

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[SEP-5] Using Mathematics and Computational Thinking [SEP-6] Constructing Explanations (for science) and Designing Explanations (for engineering) [SEP-7] Engaging in Argument from Evidence [SEP-8] Obtaining, Evaluating, and Communicating Information	LS2.A: Interdependent Relationships in Ecosystems LS2.C: Ecosystem Dynamics, Functioning, and Resilience LS4.A: Evidence of Common Ancestry and Diversity LS4.C: Adaptation ESS2.D: Weather and Climate ESS2.E Biogeology ESS3.C: Human Impacts on Earth Systems ESS3.D: Global Climate Change ETS1.B: Developing Possible Solutions	[CCC-1] Patterns [CCC-2] Cause and Effect [CCC-3] Scale, Proportion and Quantity [CCC-4] System and System Models [CCC-7] Stability and Change

LIVING EARTH VIGNETTE 7.1: ANALYZING THE PAST, PRESENT, AND FUTURE OF MARINE MAMMAL EVOLUTION

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

CA CCSS Math Connections: S-ID.1, 6, 9; S-IC.6; MP.1, MP.2, MP.4, MP.7

CA CCSS for ELA/Literacy Connections: W.9–10.1a–f, 6; SL.9–10.1a–d, 4; RST.9–10.1, 3, 7, 9; WHST.9–10.1a–e, 6, 7, 9

CA ELD Connections: ELD.9–10.P1.1, 3, 6, 10

Introduction

Climate is an environmental factor from the geosphere that has a strong impact on populations in the biosphere. In this vignette, students examine how both year-to-year fluctuations in weather conditions and longer-term trends in climate have affected marine mammal populations. They analyze a variety of data sets, including fossils, amino acid sequences, population census, and temperature reconstructions over geologic time to identify patterns and correlations that provide clues to cause and effect relationships. Students are expected to integrate their knowledge of Earth systems and ecosystems as the changes introduced involve complex interactions among plate motions, climate, human activities, evolution, and population dynamics. While the data sets provide clues, there are no easy answers in this vignette—evidence supports many possible interpretations and no simple model is sufficient to explain all the observations. This complexity and uncertainty make the vignette an ideal culmination of the Living Earth course.

Length and position in course: This vignette describes two to three weeks of instruction that integrate many aspects of the Living Earth course.

Teacher background: Marine mammals include three different types: whales and dolphins (infraorder *Cetacea*), manatees and dugongs (order *Sirenea*), and seals and sea lions (clade *Pinnipedia*). Each type occurs at a different level of taxonomy. For simplicity, this activity refers to each by their common names. Despite their many similarities, these organisms evolved independently from different land mammals around the same times and in response to the same environmental conditions.

5E Lesson Design: This sequence is based on an iterative 5E model. See chapter 11 on instructional strategies in this framework for tips on implementing 5E lessons.

LIVING EARTH VIGNETTE 7.1: ANALYZING THE PAST, PRESENT, AND FUTURE OF MARINE MAMMAL EVOLUTION

Day 1: Problems Affecting Diverse Marine Mammals

Students are introduced to local challenges to marine mammals. They obtain and evaluate information about three different types of marine mammals. They ask questions about whether their similarities were inherited from a common ancestor.

Day 2: Fossil Evidence for Evolution

Students analyze a sequence of fossils, using patterns to trace the evolution of different marine mammals back to different land-dwelling ancestors.

Day 3: DNA Evidence for Evolution

Students analyze sequences of amino acids to determine relative similarity between the DNA of different marine and land-dwelling animals. DNA evidence confirms that the three different marine mammal species evolved separately from one another.

Days 4–5: Animals Evolve in Response to Climate Change

Students ask questions about the influence of climate changes on the evolution and biodiversity of different marine mammal species. They obtain information to support claims about complex cause and effect chains: changes caused by plate motion in the shape of ocean basins that caused changes in ocean currents that caused changes in climate that influenced evolution.

Days 6–7: Predicting Future Climate Impacts

Knowing that marine mammal species have been so strongly influenced by climate changes in the past, students analyze data about shorter-term impacts from El Niño on sea lion populations.

Days 8–10: Human Impacts and Human Solutions

Students obtain information about the extinct Steller’s sea cow to debate whether climate changes or human impacts caused its downfall. They evaluate different design solutions to protect modern day marine mammal populations.

Day 1: Problems Affecting Diverse Marine Mammals (Engage)

Anchoring phenomenon: In 2015, marine mammal experts rescued three times the usual number of stranded sea lion pups on Southern California beaches.

Students watched a video that introduced the anchoring phenomenon about record numbers of sea lion pups rescued on Southern California beaches. The movie claimed that the mystery remains unsolved, but climate change may be to blame. Students discussed initial ideas about how climate change could have played a role. On the road to evaluating this claim during subsequent days, students investigated how marine mammals responded to ancient climate shifts and then analyzed recent trends.

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To ensure that students had some basic background knowledge about the diversity of marine mammals, Mr. T organized a jigsaw during which each student **obtained information [SEP-8]** to become experts about one of the three major types of marine mammals: seals (*Pinnapedia*), whales and dolphins (*Cetacea*), and manatees (*Sirenia*). Experts shared all sorts of facts: where they live, what they eat, how they gather food, how big they are, how they sleep, how they breathe, their mating habits, and more. Groups with an expert on each type **evaluated their combined information [SEP-8]** by making a Venn diagram comparing the three types. Mr. T then had students **develop questions [SEP-1]** about the evolutionary history of marine mammals by looking at the diagram. When did each type of marine mammal evolve? What environmental factors caused them to evolve this way? How do marine mammals relate to regular land dwelling mammals? Is it possible that all these organisms evolved from a common ancestor that had the features at the center of the Venn diagram?

Day 2: Fossil Evidence for Evolution (Explore)

Investigative phenomenon: The ancestors of ancient marine mammals have slowly changed over time (in both body shape and the shapes of external structures).

Scientists trace the evolutionary history of animals using a range of tools, including fossils. On day 2, students reconstructed the evolutionary sequence of each type of marine mammal. Mr. T provided each expert team a stack of cards. Each one showed a diagram of a complete skeleton of an ancestor to the team's marine mammal. The top card was the modern-day skeleton but all the rest of the fossils were in random order; the students had to put them in their correct evolutionary sequence. Mr. T explained that this process was quite different from the way paleontologists complete their work—each fossil came from a layer of rock in a known sequence and often a known age. The jumbled sequence, he explained, helps students pay close attention to the gradual progressions that exemplify many evolutionary changes. Students related these gradual progressions back to the initial questions they developed in day 1. Students did not need to understand much about marine mammal anatomy—their goal was to **analyze [SEP-4]** **patterns [CCC-1]** such as the tail is getting longer or the teeth are shrinking.

Mr. T had them tape their cards along the wall in sequence and add sticky notes to emphasize features that changed from frame to frame. Students then returned to their mixed jigsaw groups to lead tours of their fossil sequence to experts from other groups. Mr. T asked the students to evaluate if all the fossil sequences started from a common ancestor. They discovered that all three of these marine mammals evolved from land mammals that walked on four legs and had long tails, each one from a distinctly different looking creature. Seals evolved from something like an otter while the ancestor of the whale was the size and shape of something like a cross between a dog and a very large rat. Students ended the day by reflecting on what they had discovered by writing a brief **argument [SEP-7]** refuting the statement, "Whales, manatees, and seals all evolved from a common ancestor." What

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evidence would they expect to find if this statement were true? Did they find that evidence? The shared traits of these different marine mammals exemplify convergent evolution.

Day 3: DNA Evidence for Evolution (Explore)

Convergent evolution is easy to notice, but how does it happen? On day 3, students learned how genome mapping illustrates the evolutionary history of organisms. To review what students learned earlier in the year about DNA and heritability, Mr. T wore a geeky science t-shirt that said: “98 percent Chimpanzee” on the front and “50 percent banana” on the back. He began class by asking students to explain the shirt’s joke. He then had students do a think-pair-share in which they responded to the questions: What are the implications of humans being 98 percent chimpanzee? What does this information allow us to predict about humans and chimps.

Investigative phenomenon: The amino acid sequence in the protein cytochrome C is similar for many animals, but there are notable differences.

Mr. T informed them that they would do some simple analysis of DNA sequences to see how numbers like these percentages on his t-shirt were constructed. He gave a short mini lecture on genome mapping and genetic barcoding. Students needed enough basic background to interpret data from genome mapping of marine mammals to infer how closely related two organisms were. He provided lab teams with amino acid sequences of a protein common to many organisms, cytochrome C.[7] The list contains about two-dozen animals. The DNA of a grey whale was identified at the top of the list, but the rest were simply labeled “Organism A, B, C, etc.” Like the previous day, they focused on the **pattern [CCC-1]** of the amino acids rather than trying to understand the details. Students tried to arrange the organisms in order of how closely related they were to the grey whale. Mr. T then revealed the actual organisms (including fungus, wheat, dog, and penguin). Students discovered that, at least for this one protein, the grey whale is more closely related to cows than it is to seals or manatees. While this is just one small section of DNA, it confirms the fossil evidence that the organisms evolved from different species of land animals rather than a single common marine ancestor. Mr. T had students return to their previous day’s **argument [SEP-7]** and extend it with the new DNA evidence (HS-LS4-1).

7. Evolution & the Nature of Science Institutes. 2001. “The Cytochrome-C Lab.” http://www.cde.ca.gov/ci/sc/cf/ch7.asp#link167; Students can also learn to access proteins from mapped genomes directly from the National Center for Biotechnology, “Cytochrome C Southern Elephant Seal.” http://www.cde.ca.gov/ci/sc/cf/ch7.asp#link168

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Days 4–5: Animals Evolve in Response to Climate Change (Explain)

Investigative Phenomenon: Three separate species of land mammals all evolved to become entirely aquatic organisms.

Whatever the genetic mechanism, three separate species of land animals all evolved to become entirely aquatic organisms. Why? The general trend in evolution has been for organisms to emerge from the water, so what conditions led the three marine mammal types to return? Mr. T had students begin by writing a short story that described a possible scenario that would explain why separate land animals returned to the ocean. He invited them to be creative with their ideas, but they needed to be consistent with the previous concepts they had learned in the class. What sort of evidence did they expect to find if their story is true? They revisited their story at the end of this activity.

Investigative Phenomenon: The diversity of marine mammals has shrunk and grown over the last 60 million years.

Students returned to fossil evidence to look at when each species evolved. They plotted and **analyzed data [SEP-4]** showing the number of genera of each type of marine mammal alive at different points in geologic time (figure 7.15). Students analyzed one marine mammal in jigsaw groups before coming together to compare them.

Figure 7.15. Diversity of Marine Mammals Over the Last 60 Million Years

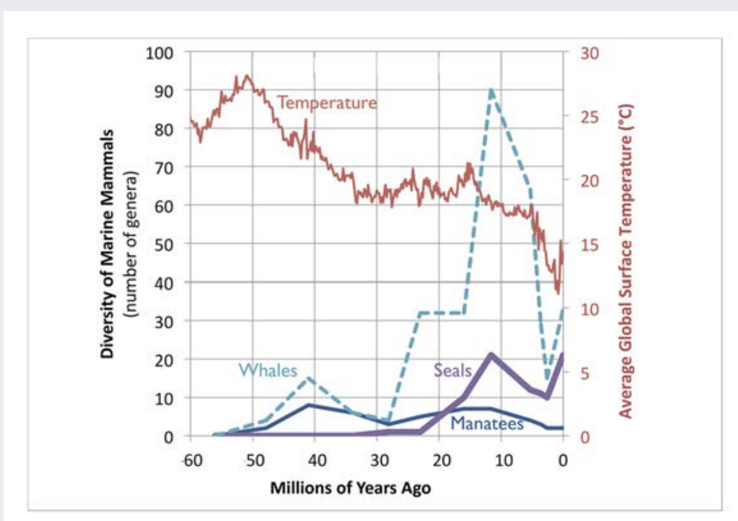

Chart by M. d'Alessio with data from Uhen 2007 and Hansen et al. 2013
Long description of Figure 7.15.

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Students found that whales and manatees evolved at nearly the exact same time ~50 million years ago, thrived for about 10 million years, and then started to die off. The diversity then exploded dramatically to a peak around 10 million years ago (around the same time that seals first evolved), only to have all three types of marine mammals collapse simultaneously a few million years later. Mr. T invited students to ask testable questions about why these creatures shared such a similar history even though they evolved independently. Groups asked things like, "Did they evolve at the same time because a new food source evolved in the ocean?" and "Did they start to die out because of an asteroid?" Mr. T focused on the group that asked, "Was there something about the environment that changed at 50 million years ago?" He asked them what sort of physical changes could occur, and climate was one possibility.

Investigative Phenomenon: Some of the changes in marine mammal diversity occur at the same time as major changes in global temperature.

Mr. T provided the class with another graph showing a reconstruction of global temperatures. Students used the graphs to present possible explanations of some of the changes in biodiversity (HS-LS2-2, HS-LS4-5). Could whales and manatees have escaped into the water to avoid exceptionally high temperatures at the time? Or did the warmer temperatures simply make food sources more abundant in the ocean? Could the expansion of all marine mammals starting around 18 million years ago (Ma) be related to a slight warming known as the Middle Miocene Climatic Optimum (perhaps causing an explosion in ocean productivity)? Could the collapse shortly thereafter be related to the cooling trend a few million years later? Students read some short articles and Mr. T provided a mini-lecture to help students understand the relationship between temperature and marine biological productivity and how this relates to what may have happened during the Middle Miocene Climate Optimum. Mr. T had students draw a concept map (a pictorial **model [SEP-2]**) illustrating some of the cause and effect relationships they saw in the data (figure 7.16).

Figure 7.16. Concept Map Illustrating Cause-and-Effect Relationships

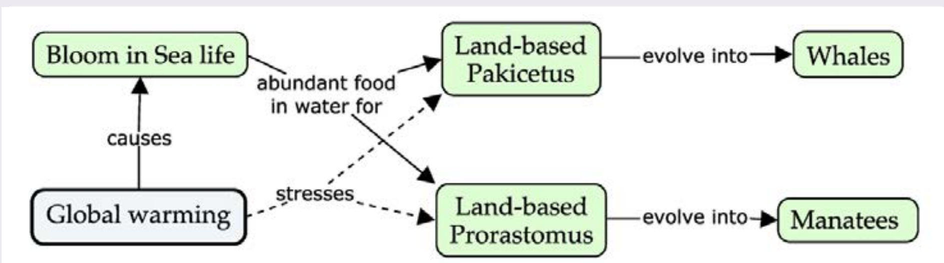

Diagram by M. d'Alessio
Long description of Figure 7.16.

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When students saw cause and effect relationships between climate change and biodiversity, they also wondered about what caused such dramatic climate fluctuations. Mr. T had students discuss an article that described some surprising ties between the motion of Earth's tectonic plates and climate. For example, when the Tethys Sea closed sometime between 20 and 15 Ma, it may have disrupted global wind and ocean currents so much that the planet began a dramatic cooling. That cooling affected marine mammal diversity. After the reading, Mr. T had students extend their concept map model (figure 7.17) showing the complex chain of **cause and effect [CCC-2]** (7.17A and B). He had them use their diagrams to **debate the claim [SEP-7]** that "whales would not have evolved without plate tectonics." (HS-ESS2-7). Students finished the activity by returning to their stories from the beginning of day 4. Did their stories match the evidence?

Figure 7.17. Extended Concept Map Showing Chains of Cause and Effect

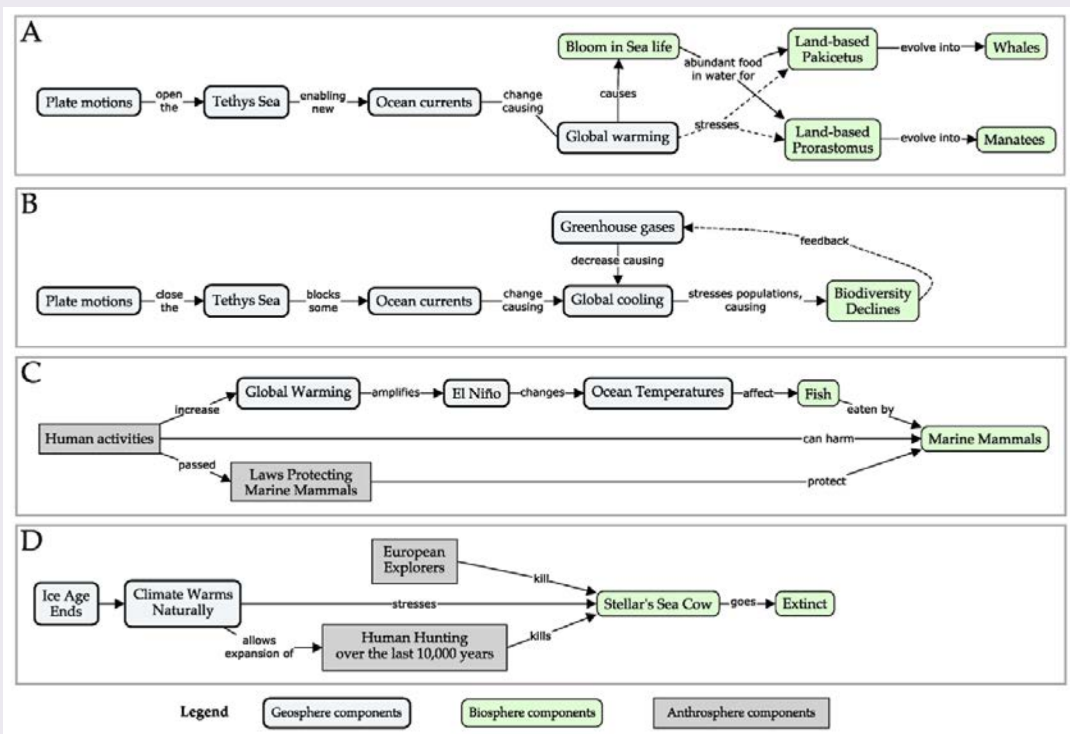

Diagram by M. d'Alessio

Long description of Figure 7.17.

Days 6–7: Predicting Future Climate Impacts (Explain)

The entire history of marine mammals in the past depends in part on changes in the climate, but how will future climate change affect today's populations? While the effects of long-term climate change are hard to model, short-term changes to global temperature are becoming increasingly common due to El Niño. Examining the effects of these short-term changes provides insight into the ways ecosystems might respond to longer-term changes. Students

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returned to questions from day 1 about sea lion populations. They used a spreadsheet to plot and **analyze [SEP-4]** sea lion population over the last 40 years (figure 7.18).

Figure 7.18. Sea Lion Pup Population and El Niño Intensity

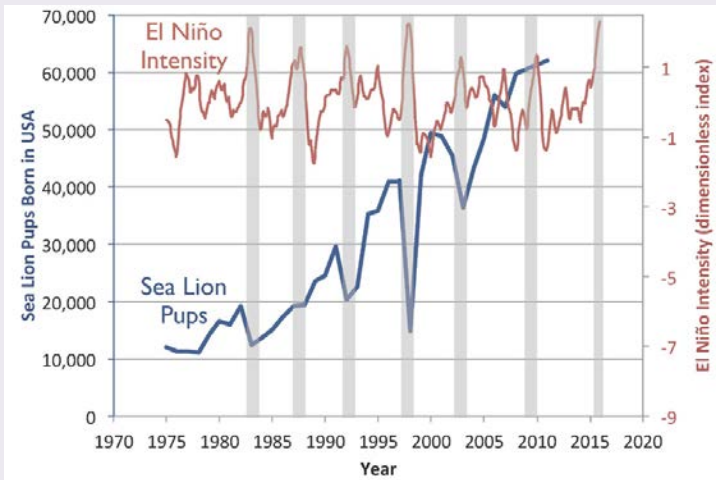

Chart by M. d'Alessio with data from National Oceanic and Atmospheric Administration Fisheries 2015 and Climate Prediction Center 2015
Long description of Figure 7.18.

Investigative Phenomenon: Sea lion populations have increased over the last 40 years but seem to undergo population collapses every few years.

Students recognized two important features in the data: (1) sea lion populations have generally increased since the mid-1970s; and (2) every few years, there is a sudden reduction in the number of sea lion pups. They considered the overall growth trend on day 7, but on day 6 they focused on the **cause [CCC-2]** of the periodic reductions. Students discovered that sea lion pups tend to suffer severe die-offs in years when El Niño is extreme. They began to create a model for the exact mechanism by which El Niño affects sea lions by graphing the availability of their favorite food sources, fish such as sardines and anchovies (see California Academy of Sciences 2015). Since the cause and effect chains have many steps, students continued to use concept maps to record their understanding, building part of 7.17C. They used their model to evaluate the claim that El Niño's fluctuations have caused changes in the sea lion populations (HS-LS2-6). Students plotted data from the amount of fish caught by commercial fishermen, so Mr. T also led a discussion about how these changes not only impact sea lions, but they also impact human populations (EP&C I).

Students then read articles to **obtain information [SEP-8]** about computer simulations that predict how El Niño would change as climate changes. Some models show that El Niño would probably not occur more frequently, but the intensity of El Niño and La Niña might

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increase, causing larger fluctuations from year to year (HS-ESS3-6; EP&C III). Will sea lions be able to adapt to these **unstable [CCC-7]** conditions? Students added their new understanding of cause and effect to their concept map models.

Day 8: Human Impacts (Elaborate)

Students noticed that the population of sea lions in the United States had been growing steadily since the 1970s. Could this be related to climate change? The small but steady temperature increases in the ocean were unlikely to be strong enough to have such a dramatic impact. What besides climate could have such a dramatic impact on animal populations? Human activities. The United States Congress passed the Marine Mammal Protection Act in 1972, which makes marine mammal conservation a priority. Mr. T told students that this act was put in place in time to protect sea lion populations, but it was not early enough to save all of California's marine mammals. The fossil record reveals one more exciting surprise.

Investigative Phenomenon: Fossils indicate that Steller's sea cows, giant manatees, once lived off of California. These organisms were last seen alive by explorers in the 1700s near a remote island in Alaska but have since become extinct.

Students reviewed videos and Internet resources to **obtain information [SEP-8]** about the Steller's sea cow, finding that it is the largest manatee species known (growing up to 9 meters long—nearly three times the size of Florida's well known manatees). When explorers first encountered it in 1741, it was abundant but only found in a few isolated pockets around uninhabited islands off the far western tip of the Aleutian Islands near Russia. Within 27 years of its discovery by Europeans, it was hunted to extinction. The Steller's sea cow was the last branch of a genetic tree that diverged from the rest of the manatee and dugong family more than 20 million years ago. As recently as 20,000 years ago, it extended along the rim of the North Pacific as far south as Japan and Monterey Bay in California. Since they only survived in places without human civilization, some scientists speculate that human hunting in the last 10,000 years contributed to their demise. Others note a number of other species also died out in that time period because of a major shift in climate at the end of the last ice age. Students **collected evidence and engaged in a debate [SEP-7]** about whether early humans, European explorers, or natural climate change were most responsible for their extinction (EP&C II). To prepare for the debate, students constructed a concept map model to represent the different possible causes of the extinction (7.17D). Mr. T also prompted students to investigate the rate of **change [CCC-7]** in the last 10,000 years versus some of the other changes in the evolution of marine mammals they learned about on previous days.

Days 9–10: Human Solutions (Evaluate)

Students had been posting their concept map diagrams and their data plots on the walls around the classroom throughout the week. To evaluate whether or not students could link

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their evidence to their model, Mr. T highlighted one specific relationship on a concept map and asked a student to point to the specific feature in a specific graph or informational article that provided evidence for this link. He repeated this prompt for a variety of linkages on the concept maps and then reversed the process by holding up a graph and asking students to identify where its interpretation was represented on the concept map models.

Investigative Phenomenon: How can people reduce their impact on marine mammal populations? .

Students finished this instructional segment evaluating competing design solutions for reducing human impacts on marine mammal populations (HS-ESS3-4, HS-ETS1-3). Mr. T asked his students to decide between two possible challenges: preserving habitat for seals and sea lions in coastal California or managing overfishing in the waters of the Gulf of California where humpback whales birth their calves. He presented teams with handouts that allowed them to **define the problem [SEP-1]**, including pressures from human activities and climate change. Different teams received handouts identifying one of several different alternatives and students created a presentation **communicating [SEP-8]** the pros and cons of the plan (EP&C V). The students continued this activity the following week.

Vignette Debrief

As the culmination of the entire course, this vignette showed how the biosphere, geosphere, and anthrosphere interact.

SEPs. A major focus of the vignette was on having students **analyze [SEP-4]** different data sets and notice that they exhibit **patterns [CCC-1]**. These correlations invited students to **ask questions [SEP-1]** about possible **cause and effect relationships [CCC-2]**. The evolution of marine mammals presented sequences of complex chains of cause and effect relationships, so the vignette relied on concept maps as pictorial **models [SEP-2]** to represent them. Students used these models to help structure **arguments [SEP-7]** such as the debate on day 8 and the assessment on day 9.

DCIs. Students examined evidence of common ancestry from homologous structures, fossil sequences, and DNA similarity (LS4.A) in the first 3 days of the lesson. They then sought to explain the evolutionary sequence of land mammals migrating to the ocean in terms of adapting to environmental changes (LS2.C, LS4.C). Many of these changes were related to human impacts (ESS3.C) on global climate (ESS2.D, ESS3.D), and they used computer simulations to predict future changes to marine mammal populations on days 6 and 7 given different climate change scenarios. While the lesson emphasized how earth systems influence the evolution of biological systems, it also briefly touched upon the role biodiversity plays in maintaining the concentration of greenhouse gases in the atmosphere (fig. 7.17B; ESS3.E).

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CCCs. While students comprehend cause and effect from a very early age, the analyses in this lesson sequence demonstrated the rich and complex understanding of **cause and effect [CCC-2]** at the high school level. Students learned to use evidence to distinguish between several possible causal mechanisms and recognized that several factors may contribute with different amounts of influence. They also could model complex chains of cause and effect (as in figures 7.16 and 7.17) that also included feedback loops (as in figure 7.17D) that could reinforce or counterbalance **change [CCC-7]**. This lesson also illustrated how high school students could integrate evidence from a range of different **timescales [CCC-3]**, noticing that the short-term changes in ocean temperature from El Niño from year to year and the slow changes in global climate over millions of years can both influence populations and survival via the same basic mechanism. Abrupt changes from year to year can add up to a steady evolutionary **change [CCC-7]**.

EP&Cs. Humans have the capacity to affect marine mammals in so many ways. Humans can directly hunt and kill animals as they did with the Steller's sea cow (day 8, EP&C II), but they can also alter natural systems (EP&C III) so strongly that they influence the climate. In addition to having to adapt to the changes in their own living conditions, climate change can also disrupt food supplies such as marine fish such that humanity suffers much like the sea lions pups (EP&C I). As students explored some of these impacts on days 8–10, they designed solutions that had to meet the long-term needs of society and the ecosystem as well as being tolerable in the short term for society (EP&C V).

CA CCSS Connections to English Language Arts and Mathematics. Throughout the instructional sequence, students participated in pair, group, and whole class discussions (SL.9–10.1a–d). They engaged in reading informational texts to identify key pieces of evidence (RST.9–10.1, 3, 7, 9). The students also produced several types of writing including an argument and a short story (WHST.9–10.1a–e, 6, 7, 9). In the vignette, students were also asked to analyze several data sets looking for patterns and possible causes for population changes (S-ID 1, 6, 9; S-IC 6) Students were also asked to create a formal presentation to exhibit their findings (SL-9–10.4.a).

Resources:

Climate Prediction Center. 2015. Oceanic Nino Index. https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link19

Hansen, James, Makiko Sato, Gary Russell, and Pushker Kharecha. 2013. "Climate Sensitivity, Sea Level and Atmospheric Carbon Dioxide." *Philosophical Transactions of the Royal Society A* 371 (2001).

National Oceanic and Atmospheric Administration Fisheries. 2015. "California Sea Lion (Zalophus Californianus): U.S. Stock." Silver Springs, MD: NOAA Fisheries. https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link20

Uhen, Mark D. 2007. "Evolution of Marine Mammals: Back to the Sea after 300 Million Years." *The Anatomical Record: Advances in Integrative Anatomy and Evolutionary Biology* 290 (6): 514–522.

Chemistry in the Earth System: Integrating Chemistry and Earth and Space Science

Introduction

This course explains how chemical processes help drive the Earth **system [CCC-4]**. Earth and space scientists require a strong background in the fundamentals of **matter [CCC-5]** and chemistry in order to interpret processes that shape the Earth system. A raindrop falls through the air, interacting with the CO_2 and becoming slightly acidic. Water that would have simply flowed through rock, if neutral, now reacts with the minerals in the rock and turns them into clay that will easily erode. Ocean water reacts with volcanic rocks on the ocean bottom so that their physical properties **change [CCC-7]** completely. When these rocks are dragged down into the Earth along plate boundaries, minerals that were once strong enough to withstand great forces now act as lubricants along this great plate boundary fault system. Heat generated deep within the Earth flows outward by conduction and convection, working to equalize the temperature difference between Earth's interior and outer space. This expression of thermodynamics turns an otherwise dead planet into a hotbed of geologic activity plagued by volcanoes and earthquakes. In each case, an Earth or space scientist is studying the chemistry of the situation, perhaps using a computer model to fast forward millions of years of chemical reactions to explain 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.

Chemistry 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. Everything in the world is made of matter and chemists study matter. In fact, Earth and space science applications are excellent motivations to the study of physical laws. Earth science can be a door into chemistry.

Even a chemistry 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 California Next Generation Science Standards (CA NGSS). Districts should be mindful and allocate resources to professional learning 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.

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 should be relevant to the students 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. 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 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.

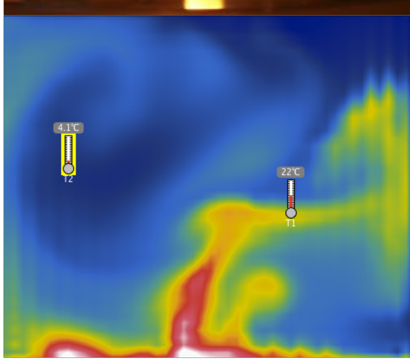
This example course is divided into instructional segments (IS) centered on questions about observations of a specific phenomenon. Different phenomena require different amounts of investigation to explore and understand, so each instructional segment should take a different fraction of the school year. As students achieve the performance expectations within the instructional segment, they uncover **disciplinary core ideas (DCIs)** from physical science, Earth and space science, and engineering. Students engage in multiple practices in each instructional segment, not only those explicitly indicated in the performance expectations. 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.

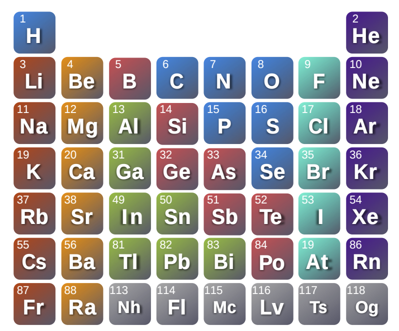
This chapter clarifies the general level of understanding required to meet each performance expectation, but the exact depth of understanding expected of students depends on this course's place in the overall high school sequence. Teachers could modify the content and complexity so that the course serves 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 Chemistry and Earth and Space Science Course

The sequence of this example course (table 7.4) is based on a specific storyline about climate **change [CCC-7]** (figure 7.19). It begins with a tangible example of combustion and food calorimetry, and indeed the combustion of fossil fuels and release of heat, carbon dioxide, and water is a fundamental thread that ties together most of the sections of the course and ensures that chemistry concepts are able to be placed in the context of Earth's systems. While many chemistry courses begin with the study of the atom, this course begins with macroscopic observations of a familiar phenomenon (combustion). The next instructional segment zooms into the microscopic, but begins with simple interactions between particles to explain thermal **energy [CCC-5]** and how it is exchanged within systems. Students then apply their understanding of heat flow to see its role in driving plate tectonics within the Earth system. Only after students are firmly thinking about matter as particles do they zoom in and look at the nature of the particles themselves by studying atoms and how their behaviors are categorized into the periodic table. Students are now equipped to model simple chemical reactions. They return to the combustion chemical reaction and consider the impact that the product of this reaction, carbon dioxide, has on the global climate system. Students consider more advanced chemical reactions and then apply their understanding of chemical equilibrium to a very real problem of ocean acidification, which is also caused by changes in carbon dioxide concentrations in the atmosphere. In the end, students will have explored the fundamentals of chemistry and essential roles that these processes play in Earth's solid geosphere, its liquid hydrosphere, and its gaseous atmosphere.

Table 7.4. Overview of Instructional Segments for High School Three-Course Model Chemistry in the Earth System

	**1 Combustion** In this brief introductory unit, students investigate the amount of stored chemical potential energy in food. They make observations of material properties at the bulk scale that they will later explain at the atomic scale. The themes of combustion and CO_2 tie together several of the instructional segments.
	**2 Heat and Energy in the Earth System** Students develop models of energy conservation within systems and the mechanisms of heat flow. They relate macroscopic heat transport to atomic scale interactions of particles, which they will apply in later units to construct models of interactions between atoms. They use evidence from Earth's surface to infer the heat transport processes at work in the planet's interior.

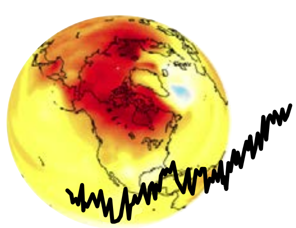


3 **Atoms, Elements, and Molecules**

Students recognize patterns in the properties and behavior of elements, as illustrated on the periodic table. They use these patterns to develop a model of the interior structure of atoms and to predict how different atoms will interact based on their electron configurations. They use chemical equations to represent these interactions and begin to make simple stoichiometric calculations.

4 **Chemical Reactions**

Students refine their models of chemical bonds and chemical reactions. They compare the strength of different types of bonds and attractions and develop models of how energy is stored and released in chemical reactions.



5 **Chemistry of Climate Change**

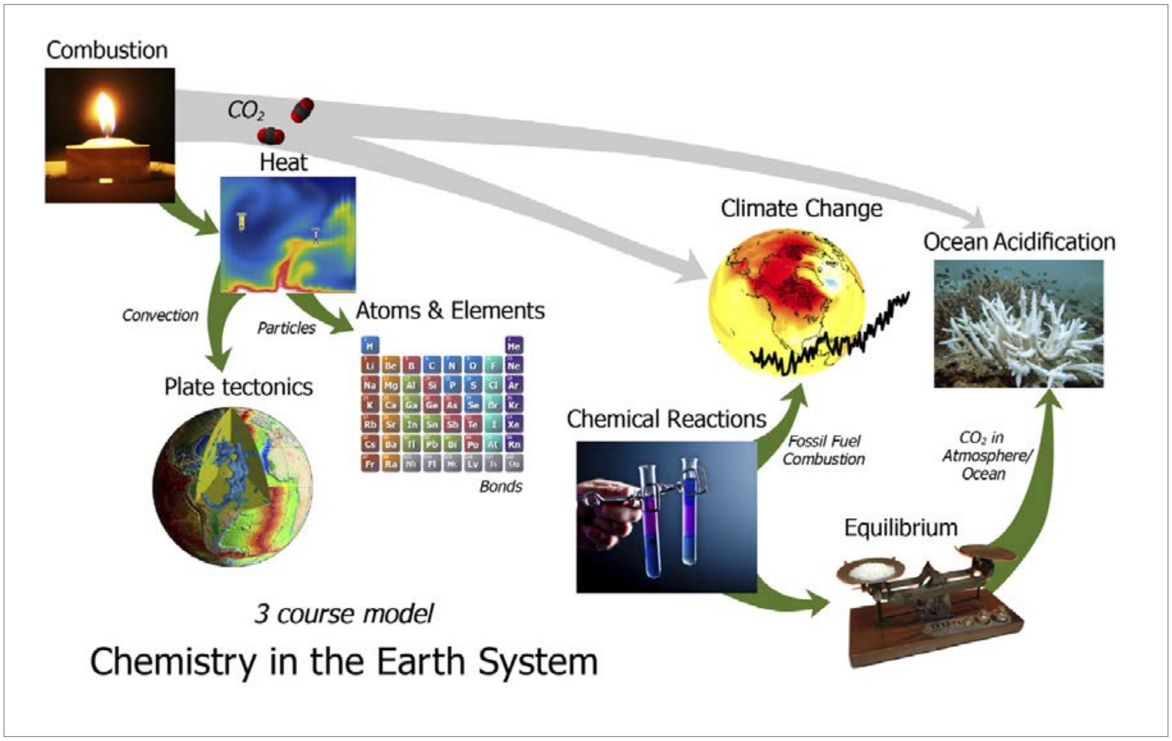
Students develop models of energy flow in Earth's climate. They revisit combustion reactions from IS1 to focus on emissions from fossil fuel energy sources. They apply models of the structures of molecules to explain how different molecules trap heat in the atmosphere. Students evaluate different chemical engineering solutions that can reduce the impacts of climate change.

6 **Dynamics of Chemical Reactions and Ocean Acidification**

Students investigate the effects of fossil fuel combustion on ocean chemistry. They develop models of equilibrium in chemical reactions and design systems that can shift the equilibrium. Students conduct original research on the interaction between ocean water and shell-building organisms.

Sources: Giardino 2006; M. d'Alessio; M. d'Alessio; Amitchell125 2011; adapted from Geophysical Fluid Dynamics Laboratory 2007; Acropora 2011; A.M. Lebow n.d.

Figure 7.19. Conceptual Flow of Instructional Segments in Example High School Chemistry in the Earth System Course



Sources: Savery 1628; Giardino 2006; M. d'Alessio; adapted from National Oceanic and Atmospheric Administration and National Centers for Environmental Information with Cooperative Institute for Research in Environmental Science 2008; adapted from NASA/Goddard Space Flight Center Scientific Visualization Studio 2002; M. d'Alessio; Amitchell125 2011; adapted from Geophysical Fluid Dynamics Laboratory 2007; Acropora 2011; A.M. Lebow n.d.
Long description of Figure 7.19.

IS1

Chemistry in the Earth System Instructional Segment 1: Combustion

Understanding chemistry allows us to understand the world around us and to make decisions and discoveries to improve the quality of life. Often we do not notice the direct influence of chemistry in our lives, but it is all around us. From the neodymium magnets that vibrate our cell phones to the chemical reactions that go on inside our bodies, chemistry is often overlooked and taken for granted. In this short introductory instructional segment, students **investigate [SEP-3]** a simple chemical system and begin to **ask questions [SEP-1]** about it. This instructional segment lays the foundation for achieving several performance expectations but is not designed in a way that students fully meet any of them upon completion. The instructional segment is instead used to set the stage for the entire course, illustrating many of the phenomena that students will investigate, model, and explain.

CHEMISTRY IN THE EARTH SYSTEM INSTRUCTIONAL SEGMENT 1: COMBUSTION

Guiding Questions

- What is energy, how is it measured, and how does it flow within a system?
- What mechanisms allow us to utilize the energy of our foods and fuels?

Performance Expectations

Students who demonstrate understanding can do the following:

HS-PS1-3. Plan and conduct an investigation to gather evidence to compare the structure of substances at the bulk scale to infer the strength of electrical forces between particles. [Clarification Statement: Emphasis is on understanding the strengths of forces between particles, not on naming specific intermolecular forces (such as dipole-dipole). Examples of particles could include ions, atoms, molecules, and networked materials (such as graphite). Examples of bulk properties of substances could include the melting point and boiling point, vapor pressure, and surface tension.] *[Assessment Boundary: Assessment does not include Raoult's law calculations of vapor pressure.]* (Introduced, but not assessed until IS3)

HS-PS1-4. Develop a model to illustrate that the release or absorption of energy from a chemical reaction system depends upon the changes in total bond energy. [Clarification Statement: Emphasis is on the idea that a chemical reaction is a system that affects the energy change. Examples of models could include molecular-level drawings and diagrams of reactions, graphs showing the relative energies of reactants and products, and representations showing energy is conserved.] *[Assessment Boundary: Assessment does not include calculating the total bond energy changes during a chemical reaction from the bond energies of reactants and products.]* (Introduced, but not assessed until IS4)

HS-PS1-7. Use mathematical representations to support the claim that atoms, and therefore mass, are conserved during a chemical reaction. [Clarification Statement: Emphasis is on using

HIGH SCHOOL THREE-COURSE MODEL CHEMISTRY IN THE EARTH SYSTEM INSTRUCTIONAL SEGMENT 1: COMBUSTION

mathematical ideas to communicate the proportional relationships between masses of atoms in the reactants and the products, and the translation of these relationships to the macroscopic scale using the mole as the conversion from the atomic to the macroscopic scale. Emphasis is on assessing students' use of mathematical thinking and not on memorization and rote application of problem- solving techniques.] *[Assessment Boundary: Assessment does not include complex chemical reactions.]* (Introduced, but not assessed until IS3. Revisited in IS4 and IS6)

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.]* (Introduced, but not assessed until IS2)

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-2] Developing and Using Models [SEP-3] Planning and Carrying Out Investigations [SEP-5] Using Mathematical and Computational Thinking	PS1.A: Structure and Properties of Matter PS1.B: Chemical Reactions PS3.A: Definitions of Energy PS3.B: Conservation of Energy and Energy Transfer PS3.D: Energy and Chemical Processes in Everyday Life	[CCC-1] Patterns [CCC-4] Systems and System Models [CCC-5] Energy and Matter: Flows, Cycles, and Conservation

CA CCSS Math Connections: N-Q.1–3; MP.4

CA CCSS for ELA/Literacy Connections: SL.11–12.5; RST.11–12.1; WHST.9–12.7, 8, 9

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

Students begin by examining nutrition labels of different foods where they will find a surprising amount of chemistry. They might notice familiar measures of mass or volume, names of chemical elements, and some ingredients with complex multi-syllabic names of chemical compounds. Students should **ask questions [SEP-1]** about what different items mean and why they are included on the label. Students are commonly familiar with the idea of Calories, but may ask what Calories are, and how they are measured. These questions drive an investigation using a standard calorimetry experiment to measure the energy output of different foods. The experiment can be done with a soda can. Students light a nut or other high-Calorie snack food on fire[8] below a metal can containing a measured amount of water. The burning food transfers energy to the water in the can. By measuring the temperature increase in the water, students calculate the amount of **energy [CCC-5]** transferred, which can be measured in the familiar unit of Calories (HS-PS3-1). The experimental results tend to be inconsistent, so different lab groups should pool their results to identify outliers before comparing their results to nutrition label values. As they **analyze the data [SEP-4]** from the whole class, they notice **patterns [CCC-1]**, such as the larger the change in food mass, the greater the temperature increase of the water. Students will investigate the detailed mechanism of that energy release related to **changes [CCC-7]** in bond **energy [CCC-5]** in IS4 (HS-PS1-4).

Students then represent this system with a pictorial **model [SEP-2]** by drawing a diagram of the components and interactions. **Energy flows [CCC-5]** represent **cause and effect [CCC-2]** relationships and students should label them as arrows with specific descriptions articulating how the energy flows from one place to another. In grade five, students calculated that mass is conserved during heating (5-PS1-2), but the mass of this chemical system appears to have **changed [CCC-7]**. Many students will incorrectly state that the mass of the food was converted to the energy of the heating (a process that only occurs in nuclear fusion). In IS4, students will revisit this system and realize that the missing atoms escaped the **system [CCC-4]** as hot gases—the products of combustion—and not because they disappeared completely (HS-PS1-7). The experimental results tend to systematically underestimate the energy of the food compared to nutrition labels. Students can use their model to speculate about the reasons for the difference.

When given time devoted to **asking questions [SEP-1]** about their experiment, students wonder if the results would differ if they used a tin can instead of an aluminum one or a different liquid instead of water, perhaps the soda that was originally in the aluminum can. This question motivates an extension to the original investigation that allows students to recognize specific heat capacity and thermal conductivity as bulk properties of substances, which they will later explain in terms of electrical forces between particles (HS-PS1-3). Students repeat the experiment using different liquids and different cans, while monitoring the temperature **change [CCC-7]** over time both while the nut is burning and afterwards as

8. This activity is an optimal time to discuss lab safety with students at the beginning of the year, including fire safety and attentiveness to nut allergies.

the liquid and the room converge to a more uniform temperature (HS-PS3-4). With careful measurements, students should discover a slight difference between freshwater and water with sugar or salt added. The difference in bulk properties must relate to some sort of microscopic interaction between the salt and the water that students will investigate in IS3.

The difference is more dramatic when they try cooking oil. (Safety reminder: students should always wear protective lab wear including goggles and aprons.) Students might wonder what the difference is between cooking oil and water that makes these materials respond to the heat differently. Before moving on, students should relate the combustion in this experiment to the real world. They should make a list of all the places that they know where things burn and they will revisit them in IS5 as they discuss the impact of burning fossil fuels on global climate (ESS3.D).

IS2 Chemistry in the Earth System Instructional Segment 2: Heat and Energy in the Earth System

As a precursor to understanding endothermic and exothermic chemical reactions, reaction kinetics, or gas laws, students need a robust model of matter moving around as discrete particles that interact. In IS2, students investigate the laws of thermodynamics in systems as small as atoms and as large as the entire Earth.

CHEMISTRY IN THE EARTH SYSTEM INSTRUCTIONAL SEGMENT 2: HEAT AND ENERGY IN THE EARTH SYSTEM

Guiding Questions

- How is energy transferred and conserved?
- How can energy be harnessed to perform useful tasks?

Performance Expectations

Students who demonstrate understanding can do the following:

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.]

CHEMISTRY IN THE EARTH SYSTEM INSTRUCTIONAL SEGMENT 2: HEAT AND ENERGY IN THE EARTH SYSTEM

HS-PS3-4. Plan and conduct an investigation to provide evidence that the transfer of thermal energy when two components of different temperature are combined within a closed system results in a more uniform energy distribution among the components in the system (second law of thermodynamics). [Clarification Statement: Emphasis is on analyzing data from student investigations and using mathematical thinking to describe the energy changes both quantitatively and conceptually. Examples of investigations could include mixing liquids at different initial temperatures or adding objects at different temperatures to water.] *[Assessment Boundary: Assessment is limited to investigations based on materials and tools provided to students.]*

HS-ESS2-3. Develop a model based on evidence of Earth's interior to describe the cycling of matter by thermal convection. [Clarification Statement: Emphasis is on both a one-dimensional model of Earth, with radial layers determined by density, and a three-dimensional model, which is controlled by mantle convection and the resulting plate tectonics. Examples of evidence include maps of Earth's three-dimensional structure obtained from seismic waves, records of the rate of change of Earth's magnetic field (as constraints on convection in the outer core), and identification of the composition of Earth's layers from high-pressure laboratory experiments.]

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 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-2] Developing and Using Models [SEP-3] Planning and Carrying Out Investigations [SEP-5] Using Mathematics and Computational Thinking [SEP-6] Constructing Explanations (for science) and Designing Solutions (for engineering)	PS3.A: Definitions of Energy PS3.B: Conservation of Energy and Energy Transfer PS3.D: Energy in Chemical Processes PS4.A: Wave Properties ESS2.A: Earth Materials and Systems ESS2.B: Plate Tectonics and Large-Scale System Interactions ETS1.B: Developing Possible Solutions	[CCC-4] Systems and System Models [CCC-5] Energy and Matter: Flows, Cycles, and Conservation

CA CCSS Math Connections: N-Q.1–3; MP.2, MP.4b

CA CCSS for ELA/Literacy Connections: SL.11–12.4, 5; RST.11–12.1, 2, 8; WHST.9–12.7, 8, 9

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

Energy [CCC-5] is perhaps the most unifying crosscutting concept in all of science. Energy is a property of both matter and radiation and is manifested as the capacity to perform work, such as causing the motion or interaction of molecules on a micro-**scale [CCC-3]**, or the movement of machines or planets on a macro-scale. Energy can be converted in form, but neither created nor destroyed. On the microscopic scale, energy can be **modeled [SEP-2]** as the motion of particles or as force fields (electric, magnetic, gravitational) that enable interactions between such particles. At the macroscopic scale, energy is manifested in a variety of phenomena, such as motion, light, sound, electromagnetic fields, and heat.

The study of thermal energy forms an important bridge between the bulk properties of matter and the atomic scale processes governing chemical reactions. In the middle grades, students developed models of matter made of moving particles, the velocity of which depends on their temperature (MS-PS1-4). In chemistry, they will learn that these particles do not just bounce off one another but can interact, and that sometimes these interactions can break up the particles into smaller constituent pieces. High school chemistry students also rely on measurements of temperature at the bulk scale to interpret chemical changes, so it is essential that students have a robust model of what temperature means. They dissolve materials in water and need to be able to extend their basic model of liquids and solids to explain what happens to both materials when they interact.

As students develop core ideas of thermodynamics, they should always be trying to understand them in the context of a model of matter as discrete moving particles. For example, The Zeroth Law of Thermodynamics states that two systems that are in thermodynamic equilibrium have the same temperature and will not exchange heat with each other. This concept follows from the claim in the middle grades that changes in motion correspond to changes in energy (MS-PS3-5). If, however, two closed systems with different temperatures are brought into thermal contact, heat will flow from the system of higher temperature to the system of lower temperature just as an object can transfer some of its kinetic energy to another object when they collide.

The first law of thermodynamics states that the total **energy [CCC-5]** of an isolated system is constant, and that although energy can be transformed from one form to another, it cannot be created nor destroyed. The **conservation of energy [CCC-5]** is thus a unifying theme in science because energy must always be accounted for in all exchanges, inviting scientists to study its flow throughout the complex biological, chemical, physical, geological, and astronomical systems they study. **Energy [CCC-5]** transfers between organisms in food webs, by wind and ocean currents on Earth, and by light from one astronomical body to another have all been a focus throughout their K–8 experience in the CA NGSS. In the middle grades, students developed specific models for describing energy transfer in moving objects (MS-PS3-5) and systems storing potential energy (MS-PS3-2).

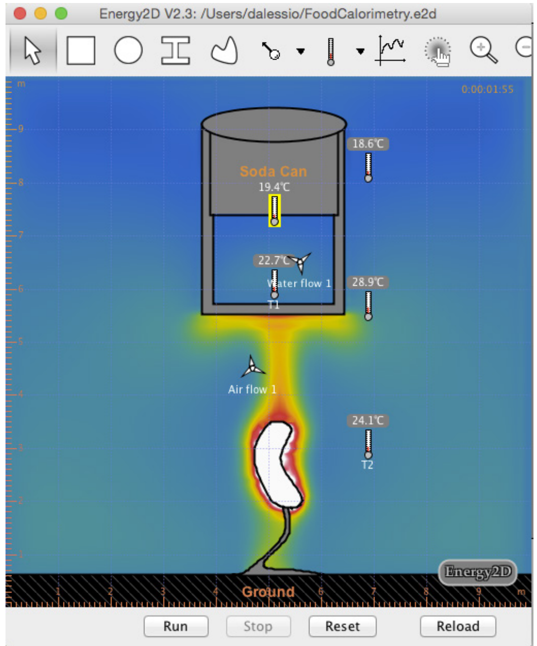
The second law of thermodynamics defines the conditions under which **energy will flow [CCC-5]** between components in a system. Isolated systems always progress toward thermodynamic equilibrium with maximum entropy. In other words, systems strive towards a uniform energy distribution among all the components. At the middle grade level, students **developed a model [SEP-2]** of individual particles that move around at speeds related to their temperature (MS-PS1-4). They also examined the forces involved in colliding objects through an engineering challenge (MS-PS2-1). Now they can combine their intuition about these two systems to enhance their **model [SEP-2]** of heat flow. If a moving car crashes into a stationary one, the moving car slows down while the stationary car receives energy and begins to move. Since **matter [CCC-5]** involves countless particles involved in countless collisions, this process repeats over and over again with the particles having more kinetic energy always transferring energy to objects with less kinetic energy. When two objects are touching, **energy [CCC-5]** is transferred in this manner until the average kinetic energy of the particles in the objects is the same. Energy continues to move back and forth during collisions, but each object gains as much as it loses during any given point in time. Students will **plan and conduct an investigation [SEP-3]** "to provide evidence that the transfer of thermal energy when two components of different temperature are combined within a closed system results in a more uniform energy distribution among the components in the system" (HS-PS3-4).

Despite the fact that a scientific model for the second law is presented earlier in this paragraph before describing the investigation, the order in the classroom would probably differ so that students do more than just verify it experimentally. An inquiry-driven investigation to monitor temperatures that culminates with a scientific **explanation [SEP-6]** resembling the second law is more consistent with the tools in chapter 11 on "Instructional Strategies" in this framework (and would definitely meet this performance expectation). Regardless of the order, students should be provided appropriate materials so that they can perform experiments such as measuring the temperature of two bodies of water before and after mixing, or the temperatures of metal blocks and water prior to, and following immersion. By repeating these **investigations [SEP-3]** with differing quantities of materials, students can apply the concept of **scale, proportion, and quantity [CCC-3]** to predict temperature **changes [CCC-7]**, equilibrium conditions, and magnitudes of energy transferred (HS-PS3-1).

At the macroscopic **scale [CCC-3]**, there are several different heat-flow mechanisms by which the second law operates: conduction, convection, and radiation. Students can relate each of these processes to the motion of individual particles (HS-PS3-2). Conduction involves the direct collision of particles, so denser materials will transmit heat faster than less dense ones. Students can **construct an explanation [SEP-6]** about why solids are much better at transferring heat by conduction than liquids or gases because of their greater density. During their **investigations [SEP-3]** of the second law, students might have noticed that heat transfer involving liquids included mixing and movement of the liquids (easily visualized with food coloring). In liquids and gases, faster moving particles can slide past or push away slower moving particles, allowing density-driven convection to occur. Radiation represents the conversion of kinetic energy to electromagnetic energy due to the movement and collisions of charged particles. Students learn more about this mechanism in the High School Three Course Model: Physics of the Universe course. Online simulations allow students to visualize each of these processes at the microscopic **scale [CCC-3]** (see PhET *Simulations* https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link21).

Computational **models [SEP-2]** are also an excellent way to explore heat transfer at the macroscopic **scale [CCC-3]**. The **investigations [SEP-3]** into the second law of thermodynamics can be done easily using free computer models designed for educational environments where students can set the material properties, geometry of systems, and initial conditions (see Concord Consortium, "Energy2D: Interactive Heat Transfer Simulations for Everyone" at https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link22). Unlike a real investigation, there are no measurement errors, the model visualization can be paused or watched multiple times, and scenarios that are impractical to study in real life can be tested easily on the computer. An excellent challenge is to have students revisit the food calorimetry experiment from IS1 and retrace the flow of heat in a computer simulation (figure 7.20). Students can observe convection, conduction, and even simulate the **effects [CCC-2]** of wind blowing through the room. To extend their **modeling [SEP-2]** of heat flow to different contexts, students can use online computational **models [SEP-2]** for simulating the **flow of thermal energy [CCC-5]** through a wall, taking into account numerous criteria such as different wall materials and different initial temperatures on both sides of the wall (HS-ETS1-4).

Figure 7.20. Heat-Flow Simulation



Visualizing heat flow using a computer simulation. Colors represent temperature at every point in the model. *Source*: Concord Consortium n.d.
Long description of Figure 7.20.

Heat Transport on Planet Earth

The drive towards thermal equilibrium operates on a massive **scale [CCC-3]** inside the Earth, with major implications for plate motions. Earth's interior is expected to be hot (from heat-generating radioactive elements in the interior), while its surface is adjacent to the cold emptiness of space. Students can **analyze [SEP-4]** temperature measurements from boreholes that show the temperature of rocks is warmer as you probe deeper into the Earth. Students can **support the claim [SEP-7]** that heat transfers from the hot interior outward. Convection is an extremely efficient heat transport mechanism that occurs when hot material rises upward because it is less dense and colder material sinks because it is denser. A simple lava lamp or any of the various published demos involving ice, warm water, and drops of food coloring are simple examples of **models [SEP-2]** of convection. Students **developed a model [SEP-2]** of convection at Earth's surface in the middle grades (MS-ESS2-6), and now they extend it to processes inside the Earth.

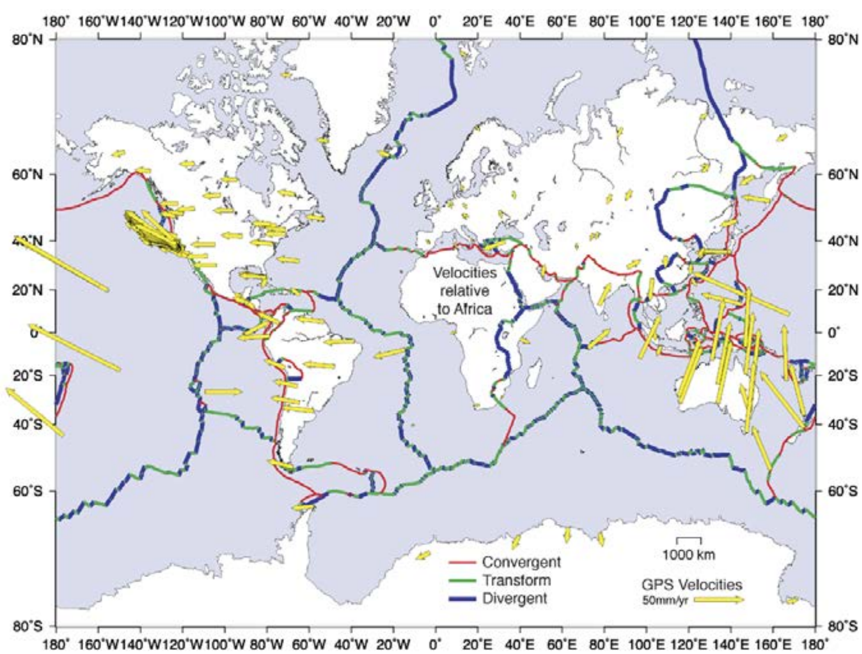
Students must **develop a model [SEP-2]** of Earth's interior and use evidence to **support the claim [SEP-7]** that its interior is convecting. Lava lamps are not perfect **models [SEP-2]** of convection in Earth's interior because there is strong evidence from seismic waves that most of the interior is not a liquid. One type of seismic wave from earthquakes, called S-waves, cannot travel through liquids. When an earthquake occurs on one side of the planet, the shaking can be recorded over a huge section of the planet as waves travel straight through the Earth. Stations on the exact opposite side of the Earth from the earthquake, however, do not record S-waves. This S-wave shadow is evidence that there is a liquid layer within Earth's core. When scientists take common Earth materials in a lab and expose them to the temperature and pressure that would exist in the core, they find that the materials do indeed become liquid when the temperature is high enough. Students can **analyze data [SEP-5]** from simplified seismograms taken from different locations around the world and identify which stations recorded S-waves and which did not. By drawing the path of seismic waves from the earthquake to each station, students can map out how big this liquid layer must be (see IRIS "Determining and Measuring Earth's Layered Interior" https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link23). The rest of the interior must therefore be solid.

If the interior of Earth is solid, how can it convect? After all, traditional chemistry textbooks claim that convection cannot occur in a solid. The paradox is resolved by coming up with a more sophisticated **model [SEP-2]** of solids and liquids that describes them on a spectrum involving both viscous and elastic behaviors rather than being two completely separate phases of matter like students may have discussed in the middle grades (MS-PS1-4). Water flows easily when poured slowly from a pitcher, but can feel painfully solid-like when a person belly flops into a swimming pool because the water cannot flow out of the way quickly enough. Polymer putty bends and oozes like a viscous fluid, but it will bounce if you throw it against a wall. Rock acts in much the same way. The forces causing convection inside the Earth push on the rock so slowly that it oozes like polymer putty. The fact that categories students have been using to describe the phases of matter do not adequately explain these behaviors of rock is an excellent example of CA NGSS's learning progression regarding patterns. While identifying **patterns [CCC-1]** and using them to classify and categorize are cornerstones of the SEPs beginning in kindergarten, by grade twelve students are expected to "recognize classifications or explanations used at one **scale [CCC-3]** may not be useful or need revision using a different scale" (NGSS Lead States 2013a). This revision process is at the heart of the nature of science.

Students can apply their **model [SEP-2]** of density-driven flow in rock not only to help understand heat transfer, but also to see how these flows give rise to plate tectonics. When hot material from Earth's interior reaches the surface, it begins to cool and becomes denser. Some of this dense material begins to sink back down, but unlike liquids in a lava lamp, the sinking solid rock is part of a connected shell of rock that forms Earth's lithosphere, its surface layer. As the dense material sinks, it drags along huge sections of the lithospheric shell with it much like an anchor pulls a rope attached to it as it sinks. A huge section of lithosphere dragged along as a single chunk is what we call a *plate*, and the movement of plates is what we call *plate tectonics*.

There are many pieces of evidence that this motion is occurring: For one, scientists can directly observe these motions using modern day Global Positioning System (GPS) measurements (figure 7.21). One **pattern [CCC-1]** revealed in such measurements is that large sections of the Earth all move together in the same direction at the same time (what we call plates). This measurement technology has only been available since the late 1980s, but scientists were able to observe other evidence that this motion is occurring by looking at the age of the seafloor (figure 7.22). There are long stripes down the middle of many oceans with very young seafloor in the center of the ocean basins and a clear **pattern [CCC-1]** where the ages are symmetrically older in both directions away from the stripe of youngest rocks. Students should be able to use seafloor ages and surface motion rates as evidence that convection occurs in Earth's interior. They can **communicate [SEP-8]** their **argument [SEP-7]** with a pictorial **model [SEP-2]** of Earth's interior that has annotations to indicate how heat transfer drives movement within the Earth (HS-ESS2-3).

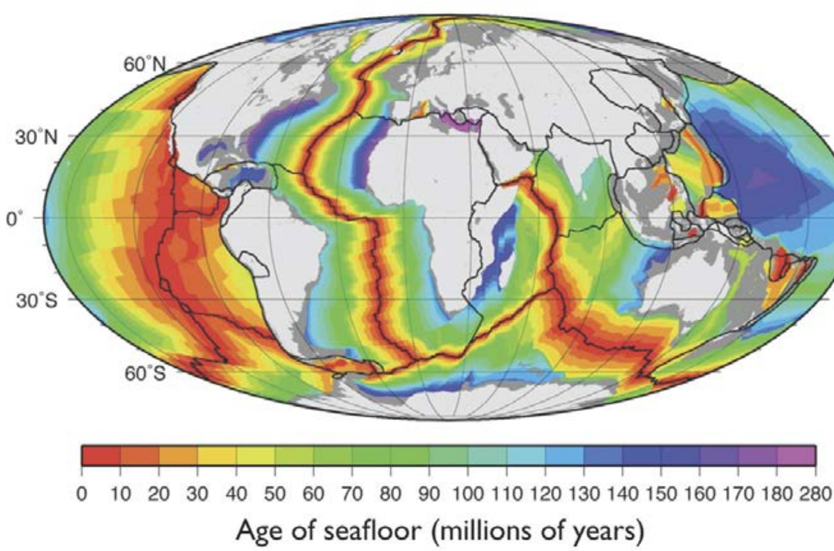
Figure 7.21. Present-Day Plate Motions



GPS velocities recorded at stations around the world reveal present-day plate motions. Arrow size relates to the speed of each point. Image credit: M. d'Alessio n.d.
Long description of Figure 7.21.

The mechanism causing new seafloor to form is another example of density-driven flow. When two plates move apart from one another, the release of pressure allows solid material to expand slightly, causing decompression melting. The melted magma is less dense than the surrounding solid rock, so it quickly rises and forms new sections of lithosphere. As the plates continue to move, this rock gets older and is dragged further from the plate boundary.

Figure 7.22. Seafloor Age



Seafloor age. Hot material from the mantle rises up and cools to form new rock material (with age of zero) at the areas shown in red. *Source*: National Oceanic and Atmospheric Administration, National Centers for Environmental Information 2008
Long description of Figure 7.22.

This section on heat flow within the Earth illustrates how studying Earth and space science and physical science concepts together enriches understanding of both disciplines. In high school, students are expected to ask questions about whether or not processes that act at one **scale [CCC-3]** are also significant at different scales of observation (appendix 1 of this framework). Students' understanding of physical science benefits from studying the role of convection in the Earth because it highlights the universality of thermodynamics—principles that function at the **scale [CCC-3]** of a laboratory experiment also apply to planetary-scale systems. Students' understanding of Earth and space science benefits because students then develop models that relate the driving forces of plate motions to **energy flow [CCC-5]**. Students' understanding of both sciences benefit from taking the time to collect the evidence supporting plate motions because effective science includes both conceptual models *and* observational evidence that supports those models.

IS3

Chemistry in the Earth System Instructional Segment 3: Atoms, Elements, and Molecules

The previous instructional segment examined the thermal interactions of objects by looking at the **energy [CCC-5]** of microscopic particles that comprise them. Students observed that different materials have different thermal properties, but they do not yet have a good explanation about what causes these differences. In fact, their **model [SEP-2]** of these particles does not yet differ much from the **model [SEP-2]** they developed in grade five: objects are made of particles too small to be seen (5-PS1-1), modified slightly in the middle grades when they defined some particles as molecules that are made of groups of atoms held together in simple structures (MS-PS1-1). This instructional segment is the first time that students actually discuss what an atom is and how it can explain so many of the properties they have observed.

CHEMISTRY IN THE EARTH SYSTEM INSTRUCTIONAL SEGMENT 3: ATOMS, ELEMENTS, AND MOLECULES

Guiding Questions

- What is inside atoms and how does this affect how they interact?
- What models can we use to predict the outcomes of chemical reactions?

Performance Expectations

Students who demonstrate understanding can do the following:

HS-PS1-1. Use the periodic table as a model to predict the relative properties of elements based on the patterns of electrons in the outermost energy level of atoms. [Clarification Statement: Examples of properties that could be predicted from patterns could include reactivity of metals, types of bonds formed, numbers of bonds formed, and reactions with oxygen.] *[Assessment Boundary: Assessment is limited to main group elements. Assessment does not include quantitative understanding of ionization energy beyond relative trends.]*

HS-PS1-2. Construct and revise an explanation for the outcome of a simple chemical reaction based on the outermost electron states of atoms, trends in the periodic table, and knowledge of the patterns of chemical properties. [Clarification Statement: Examples of chemical reactions could include the reaction of sodium and chlorine, of carbon and oxygen, or of carbon and hydrogen.] *[Assessment Boundary: Assessment is limited to chemical reactions involving main group elements and combustion reactions.]*

HS-PS1-7. Use mathematical representations to support the claim that atoms, and therefore mass, are conserved during a chemical reaction. [Clarification Statement: Emphasis is on using mathematical ideas to communicate the proportional relationships between masses of atoms in the reactants and the products, and the translation of these relationships to the macroscopic scale using the mole as the conversion from the atomic to the macroscopic scale. Emphasis is on assessing students' use of mathematical thinking and not on memorization and rote application of problem- solving techniques.] *[Assessment Boundary: Assessment does not include complex chemical reactions.]* (Introduced here and revisited again in IS4 and IS6)

CHEMISTRY IN THE EARTH SYSTEM INSTRUCTIONAL SEGMENT 3: ATOMS, ELEMENTS, AND MOLECULES

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-2] Developing and Using Models [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	PS1.A: Structure and Properties of matter PS1.B: Chemical Reactions	[CCC-1] Patterns [CCC-5] Energy and Matter: Flows, Cycles, and Conservation

CA CCSS Math Connections: N-Q.1–3; MP.2

CA CCSS for ELA/Literacy Connections: SL.11–12.4; RST.9–10.7, WHST.11–12.2, 5

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

The performance expectation HS-PS1-1 requires that high school students build upon this understanding by applying the periodic table as a **model [SEP-2]** to *predict the relative properties of elements based on the patterns of electrons in the outermost (valence) energy level of atoms*. The National Research Council's *A Framework for K–12 Science Education* (*NRC Framework*) states:

> By the end of grade 12, students should understand that each atom has a charged substructure consisting of a nucleus, which is made of protons and neutrons, surrounded by electrons. The periodic table orders elements horizontally by the number of protons in the atom's nucleus and places those with similar chemical properties in columns. The repeating patterns of this table reflect patterns of outer electron states. The structure and interactions of matter at the bulk scale are determined by electrical forces within and between atoms. The stability of matter is increased when the electric and magnetic field energy is minimized. A stable molecule has less energy, by an amount known as the binding energy, than the same set of atoms separated, and one must provide at least this energy in order to take the molecule apart. (National Research Council 2012)

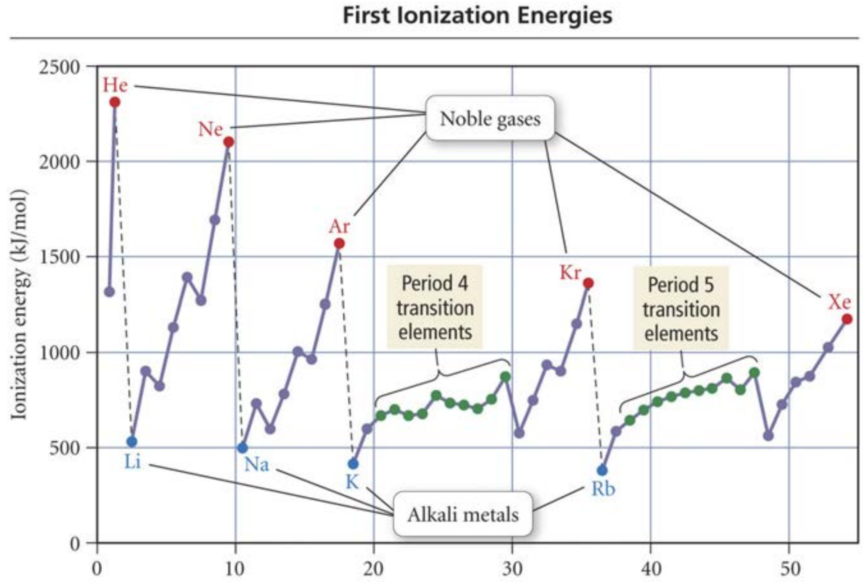
The performance expectations in the middle grades do not require students to develop a model of the atom's internal workings. This sequence differs from the 1998 California Science Content Standards in which the internal workings of the atom were introduced in eighth grade. It is conceivable that students highly proficient in the CA NGSS performance expectations for the middle grades have never heard the words *protons*, *neutrons*, and *electrons*. The CA NGSS learning progression has been designed so that this material is introduced at a time when it is developmentally appropriate and integrates with their learning in other disciplines (in this case, a formal description of electrical attraction with Coulomb's Law appears in high school physics). Students do, however, have significant experience recognizing **patterns [CCC-1]** and **asking questions [SEP-1]** about them. They have **analyzed data [SEP-4]** about the bulk properties of matter and are ready to begin relating them to the components that make up atoms.

Memorizing rules about the periodic table is not sufficient to meet HS-PS1-1. Instead, students must understand and apply underlying **models [SEP-2]** of atomic structure and interaction along with the principle of **cause and effect [CCC-2]**. They use these models to **explain [SEP-6]** why the properties of the elements **repeat in a periodic fashion [CCC-1]** and can use the periodicity to predict bulk properties of elements, their reactivity, and the types and numbers of bonds they will form with other elements.

Dmitri Mendeleev, who developed the predecessor of the modern periodic table, realized that the physical and chemical properties of elements were related to their atomic mass in a predictable, periodic way. He arranged the 63 elements known when he was working so that groups with similar properties fell into vertical columns in his table. Students can build a mental model of how the periodic table is arranged by using a physical **model [SEP-2]** as an analog. By arranging color chips from a paint store into a matrix based on color and hue, students can understand the power of such models by predicting the existence of color/hue chips that were removed from the final matrix before the chips were distributed. This exercise mirrors the process Mendeleev used to predict the existence of elements not yet known.

Patterns [CCC-1] are a key crosscutting concept because they result from underlying causes. Observed patterns not only guide organization and classification but also prompt questions about relationships and the factors that influence them, and thereby lead to a discussion of **cause and effect [CCC-2]**. When chemists organized elements in order of increasing relative atomic mass, they noticed repeating, or periodic patterns. For example, they noticed trends in chemical reactivity were punctuated by elements that were seemingly inert as shown in the high ionization energies of the noble gases in figure 7.23. These patterns led chemists to suppose that there were underlying causes that created these patterns. The recognition of these patterns thus contributed to our understanding of atomic theory, the key **model [SEP-2]** that students are expected to apply in this instructional segment. Using dynamic computer-based periodic tables, students can easily investigate a variety of properties (such as atomic radius, first ionization energy and electron affinity) and observe periodic **patterns [CCC-1]** that provide evidence of patterns in underlying atomic structure.

Figure 7.23. Patterns in the First Ionization Energy of Different Elements



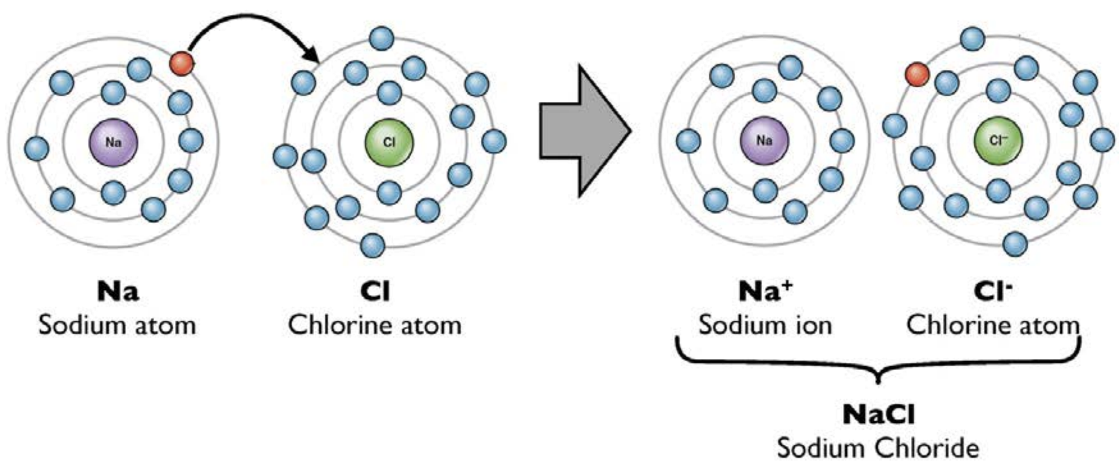
As students analyze plots of the properties of the elements as a function of atomic number, they should notice and discuss trends and patterns such as the comparatively low ionization energies of the alkali metals versus the high ionization energies of the noble gases as seen in this plot of first ionization energies. *Source*: RJHall 2010

Long description of Figure 7.23.

The practice of **developing and using models [SEP-2]** in the CA NGSS often calls for students to develop their own models based on evidence they obtain directly. It took decades for the scientific community to develop models of the substructure of atoms that explain the patterns in the periodic table. One approach to helping students develop their own models is through a historical presentation of the evidence. A historical summary demonstrates how these models were repeatedly revised following revolutionary discoveries, starting with the billiard ball model and eventually culminating in Bohr's model and our modern quantum mechanical model. This sequence parallels the learning progression outlined in the CA NGSS in which students come into high school chemistry with the billiard ball model of atoms and leave with mastery of a more modern version (a quantum mechanical model of the atom is not assessed as part of the CA NGSS, so the working model adopted by individual classrooms depends on the local context. Bohr's model produces sufficient predictive power to meet the performance expectations in the CA NGSS.) Students can make these models on their own by **obtaining information [SEP-8]** from the Internet about various analogies of atomic structure (Goh, Chia, and Tan 1994) and **evaluating [SEP-8]** the limitations of these models.

Students can then interpret the trends displayed in the periodic table in light of their underlying model for atomic structure. They relate the overall order of the periodic table to the number of protons and electrons in the atom's outermost energy level. Students can then develop a simple model of interactions between atoms based on their electron configuration (figure 7.24). They should be able to use the periodic patterns of electron configuration in the periodic table to predict properties such as the overall reactivity of metals and the number of bonds an atom can form (HS-PS1-1), as well as being able to predict the outcome of simple chemical reactions (HS-PS1-2). For example, students should be able to predict that sodium is likely to lose electrons when interacting with other elements because it has only one loosely held electron in its valence shell, as indicated by its position in the first family. Similarly, they should be able to predict that sodium will react strongly with chlorine because chlorine tends to gain electrons due to its high electronegativity associated with its nearly filled valence shell as indicated by its position in the seventh family. Finally, they should be able to predict that the resulting sodium cation and chloride anion will be attracted to each other and form an ionic bond by applying the principles of electrostatic attraction.

Figure 7.24. Models of Atomic Structure Explain Periodic Trends



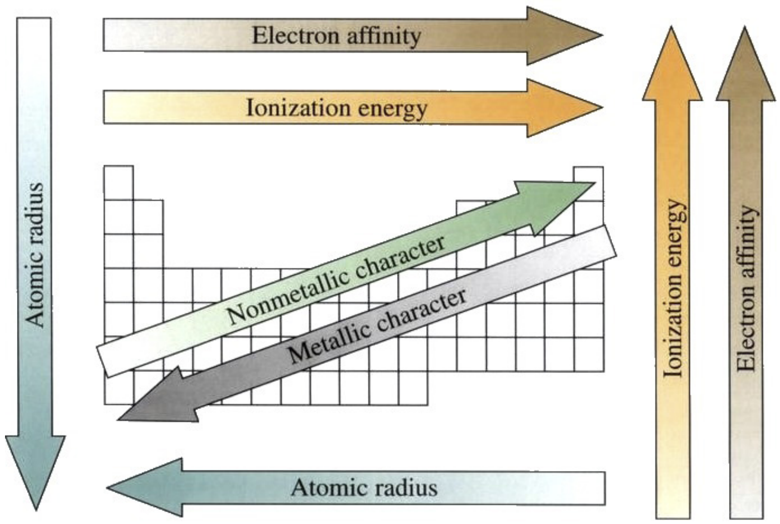
Students should predict trends within the periodic table based upon an application of models of atomic structure such as the Bohr model and octet rule illustrated here. *Source*: Adapted from OpenStax College 2013

Long description of Figure 7.24.

It is not sufficient for students to memorize and blindly apply rules for chemical bonding. Rather, they must develop **explanations [SEP-6]** for why atoms of main-group elements tend to combine in such a way that each atom has a filled outer (valence) shell, giving it the same electronic configuration as a noble gas (octet rule). To meet this performance expectation, students must describe thermodynamic principles that dictate that atoms will react with one another to transition to a more stable (lower energy) state. Filled orbitals, such as those that occur in a full octet state, are more symmetrical than other configurations, and such symmetry leads to greater stability. In addition, the electrons present in the different orbitals of the same sub-shell in a full octet can freely exchange their positions, leading to a decrease in exchange of energy and thus a lower net energy. The energy state is also affected by its electrical charge. Since opposites attract, an electrically neutral state has lower energy, and thus is more stable, than an electrically charged state. For example, students should be able to explain that table salt (NaCl) is the result of Na^+ ions and Cl^- ions bonding. If sodium metal and chlorine gas mix under the right conditions, they will form salt as the sodium loses an electron, and the chlorine gains that electron. In the process, a great amount of light and heat is released, and the resulting salt thus has much lower energy and is relatively unreactive and stable, and would not undergo any explosive reactions like the sodium and chlorine that it is made of. Students will return to this idea again when they discuss bonding energy in IS4.

HS-PS1-2 requires students to **construct explanations [SEP-6]** and **argue from evidence [SEP-7]** rather than memorize facts and trends. Students should understand the basis for **trends and patterns [CCC-1]** shown in figure 7.25 and be able to **explain [SEP-6]** the different types of chemical reactions. Once students understand the reasons for the trends observed in the periodic table, they can subsequently predict chemical reactions of significance in the physical, biological, and Earth science realms. For example, by noting that carbon is in the fourteenth family, students should conclude that it therefore has four valence electrons that can be shared by such elements as hydrogen and oxygen and explain the existence of hydrocarbons that make up fossil fuels based upon valence electron patterns. Students could also explore different mineral families and see how atoms can substitute for one another to produce gems with different colors or other properties (such as quartz which is called amethyst when small amounts of iron substitute into the crystal lattice).

Figure 7.25. Patterns and the Periodic Table



Students should understand the basis for trends and patterns in the periodic table, and be able to explain the types of chemical reactions and resulting bonds that occur between elements. *Source*: M. d'Alessio

Long description of Figure 7.25.

Cycles of Matter in Chemical Reactions

As students study these simple combinations of atoms that make molecules, students revisit the idea from the middle grades that chemical reactions rearrange atoms but **matter is conserved [CCC-5]** (MS-PS1-5, MS-LS1-7). In high school, students use chemical equations as mathematical models to illustrate the cycle of matter within these chemical systems (HS-PS1-7). Students apply these basic principles of stoichiometry through laboratory **investigations [SEP-3]**, problem solving, and reinforcement with apps and programs. The word *stoichiometry* derives from two Greek words: *stoicheion* (meaning element) and *metron* (meaning measure). Stoichiometry is based upon the law of the conservation of mass and deals with calculations about the masses of reactants and products involved in a chemical reaction. While stoichiometry can be challenging to students and teachers alike, research shows that the more time students spent in high school chemistry on stoichiometry, the greater success they had in college chemistry courses on average (Tai, Sadler, and Loehr 2005).

The law of definite **proportions [CCC-3]**, sometimes called Proust's Law, states that a chemical compound always contains exactly the same proportion of elements by mass. An equivalent statement is the law of constant composition, which states that all samples of a given chemical compound have the same elemental composition by mass. Students must learn that compounds appear in whole-number ratios of elements and that chemical reactions result in the rearrangement of these elements into other whole-number ratios. Students can develop a deeper understanding of the principles involved in HS-PS1-7 by massing and comparing the reactants and products of simple chemical reactions. For example, if students dehydrate copper sulfate pentahydrate ($CuSO_4 \cdot 5H_2O$) into the anhydrous salt ($CuSO_4$) by heating, they will find that the ratio of the mass of the resulting copper sulfate (dry mass) to water (the mass lost in dehydration) is always the same, regardless of how much copper sulfate pentahydrate is used. Students can infer that because the ratio of the component molecules in such a dehydration reaction remains constant, then the ratio of component elements must also remain constant. By applying **mathematical thinking [SEP-5]**, students learn to balance chemical reactions and predict relative quantities of products.

IS4 Chemistry in the Earth System Instructional Segment 4: Chemical Reactions

CHEMISTRY IN THE EARTH SYSTEM INSTRUCTIONAL SEGMENT 4: CHEMICAL REACTIONS

Guiding Questions

- What holds atoms together in molecules?
- How do chemical reactions absorb and release energy?

Performance Expectations

Students who demonstrate understanding can do the following:

HS-PS1-3. Plan and conduct an investigation to gather evidence to compare the structure of substances at the bulk scale to infer the strength of electrical forces between particles. [Clarification Statement: Emphasis is on understanding the strengths of forces between particles, not on naming specific intermolecular forces (such as dipole-dipole). Examples of particles could include ions, atoms, molecules, and networked materials (such as graphite). Examples of bulk properties of substances could include the melting point and boiling point, vapor pressure, and surface tension.] *[Assessment Boundary: Assessment does not include Raoult's law calculations of vapor pressure.]*

HS-PS1-4. Develop a model to illustrate that the release or absorption of energy from a chemical reaction system depends upon the changes in total bond energy. [Clarification Statement: Emphasis is on the idea that a chemical reaction is a system that affects the energy change. Examples of models could include molecular-level drawings and diagrams of reactions, graphs showing the relative energies of reactants and products, and representations showing energy is conserved.] *[Assessment Boundary: Assessment does not include calculating the total bond energy changes during a chemical reaction from the bond energies of reactants and products.]*

CHEMISTRY IN THE EARTH SYSTEM INSTRUCTIONAL SEGMENT 4: CHEMICAL REACTIONS

HS-PS1-5. Apply scientific principles and evidence to provide an explanation about the effects of changing the temperature or concentration of the reacting particles on the rate at which a reaction occurs. [Clarification Statement: Emphasis is on student reasoning that focuses on the number and energy of collisions between molecules.] *[Assessment Boundary: Assessment is limited to simple reactions in which there are only two reactants; evidence from temperature, concentration, and rate data; and qualitative relationships between rate and temperature.]*

HS-PS1-7. Use mathematical representations to support the claim that atoms, and therefore mass, are conserved during a chemical reaction. [Clarification Statement: Emphasis is on using mathematical ideas to communicate the proportional relationships between masses of atoms in the reactants and the products, and the translation of these relationships to the macroscopic scale using the mole as the conversion from the atomic to the macroscopic scale. Emphasis is on assessing students' use of mathematical thinking and not on memorization and rote application of problem- solving techniques.] *[Assessment Boundary: Assessment does not include complex chemical reactions.]* (Introduced in IS3 and revisited again in IS6)

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-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.]*

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-2] Developing and Using Models [SEP-3] Planning and Carrying Out Investigations [SEP-5] Using Mathematical and Computational Thinking [SEP-6] Constructing Explanations (for science) and Designing Solutions (for engineering)	PS1.A: Structure and Properties of Matter PS1.B: Chemical Reactions PS2.B: Types of Interactions PS3.C: Relationship Between Energy and Forces	[CCC-1] Patterns [CCC-2] Cause and Effect [CCC-5] Energy and Matter: Flows, Cycles, and Conservation

CHEMISTRY IN THE EARTH SYSTEM INSTRUCTIONAL SEGMENT 4: CHEMICAL REACTIONS

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

CA CCSS for ELA/Literacy Connections: SL.11–12.5; RST.11–12.1, 2, 8; WHST.11–12.7, 8, 9

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

Students were introduced to chemical reactions in the middle grades. In particular, they learned that substances react chemically in characteristic ways; and in a chemical process, the atoms that make up the original substances are regrouped into different molecules, and these new substances have different properties from those of the reactants. In addition, they learned that the total number of each type of atom is conserved, and thus the mass does not change; and that some chemical reactions release energy, others store energy (PS1.B). Students in the middle grades demonstrated their understanding by **analyzing and interpreting data [SEP-4]** on the properties of substances before and after the substances interact to determine if chemical reactions have occurred (MS-PS1-2), and by **developing and using models [SEP-2]** to describe how the total number of atoms does not change in a chemical reaction and thus mass is conserved (MS-PS1-5).

Chemical Bonds as Attractions Between Particles

In this instructional segment, students build upon this understanding and their newly acquired understanding of the properties and structure of matter (IS1 and IS2) to learn how elements combine to form new compounds, the forces that hold them together, the forces between particles and molecules, and the energy needed to break or form bonds. Students will expand their conceptual **model [SEP-2]** of chemical bonding, which requires a shift towards the three-dimensional learning of the CA NGSS (table 7.5).

Table 7.5. Instructional Shifts for Chemical Bonding in the CA NGSS

LESS OF …	MORE OF …
Students are told, and memorize, that ionic bonds result from the transfer of electrons from one atom to another and covalent bonds result from the sharing of electrons between two atoms. Students are then presented with differences in the two types of bonding. They conduct experiments to verify these differences.	Students observe how materials behave on their own and with other substances. They recognize **patterns [CCC-1]** that allow them to determine that there must be two different categories of materials. They use evidence about the properties to infer the strength and properties of the bonds that hold the materials together. Eventually, they label these categories with the appropriate scientific terms of ionic and covalent bonds.

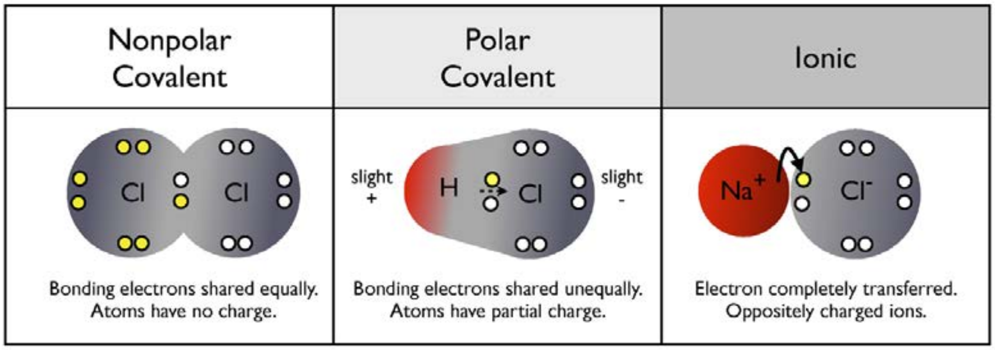
Observations at the macroscopic level give clues about the nature of chemical bonding (HS-PS1-3). When students **conduct an investigation [SEP-3]** to measure the conductivity of different solutions (salts, acids, bases, hydrocarbons, and oxides), they gather evidence that there must be some relationship between electricity and material properties.

They use this evidence to support a **model [SEP-2]** of different types of chemical bonds and attractions. When considering ionic bonds, this model includes attractions between charged particles related to Coulomb's Law, which is assessed in the high school Physics of the Universe course (HS-PS2-4 and HS-PS3-5). Students will learn how the nuclei of some atoms have enough attractive force to pull one, two, or three electrons away from another nucleus that does not have the same attractive force on its own electrons. By applying the principles of electrostatic attraction, students should be able to predict that the resulting cations and anions will be attracted to each other and form ionic bonds. However, if either ion feels a stronger attraction to a different particle, then the existing bond is easily broken. Knowing that when salt dissolves in water, its bonds are broken, what can students infer about the charge of water molecules?

Pure materials with high boiling points are more likely to be bonded together more stably than materials with lower boiling points. As two non-metals come very close to one another, the respective orbitals of the atoms overlap, trapping two electrons in the energy field, creating the covalent bond (HS-PS3-5). Differences in how these ionic and covalent bonds are created (figure 7.26) are often overlooked, resulting in oversimplified definitions. To properly **explain [SEP-6]** the link between bulk effects and microscopic **causes [CCC-2]** (HS-PS1-3), students must develop robust models of how these bonds form.

Students can also **investigate [SEP-3]** other forms of attraction such as polar attractions and intermolecular forces. The clarification statement of HS-PS1-3 specifies that students do not need to refer to these attractions by name, but they should be able to investigate properties like surface tension and viscosity and provide a model-based explanation of how these properties relate to microscopic electromagnetic attractions.

Figure 7.26. Covalent, Polar Covalent, and Ionic Bonding



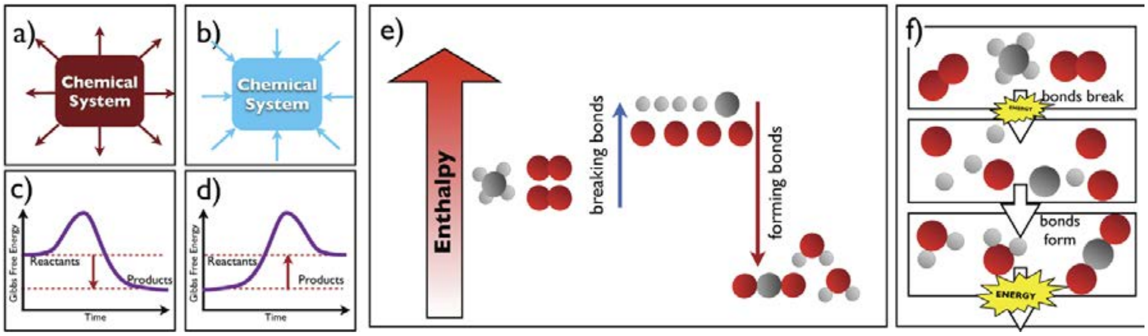
Students should be able to develop and explain models of covalent, polar covalent, and ionic bonding.
Source: M d'Alessio
Long description of Figure 7.26.

Energy in Chemical Bonds

From their work in the middle grades, students know that chemical reactions can absorb and release energy (MS-PS1-6), but they did not develop a model of the mechanisms of this energy release. HS-PS1-4 requires students to **develop models [SEP-2]** that illustrate the **release or absorption of energy [CCC-5]** from chemical reactions. They begin their model development by relating back to investigations at the bulk scale. Students can build on their model of the ionic bond breaking between sodium and chlorine when salt is dissolved in water. They can observe the water temperature decrease when they add salt, even when both materials start at the same temperature. Does breaking the bond absorb energy from the water? When sodium mixes with water, students observe that it gives off a dramatic amount of energy as light and sound. Does sodium release energy when it forms new bonds?

Students are now ready to use graphs, diagrams, and drawings to **model [SEP-2]** changes in total bond energy, such as those shown in figure 7.27 and use these tools to explain energy changes accompanying chemical reactions. The models in figure 7.27, like many pictorial models that appear in textbooks, were drafted by scientists. The models that those scientists produced when they were students were unlikely as simple and complete as these final products, but they refined their models over the years. Revising **models [SEP-2]** is an integral part of the nature of science.

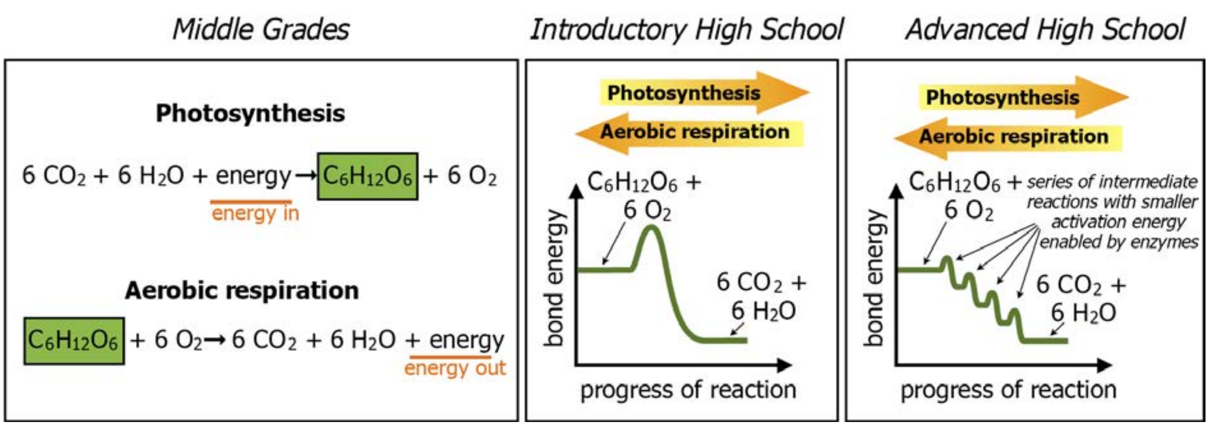
Figure 7.27. Models of Energy Changes in Chemical Reactions



Examples of a range of graphs, diagrams and drawings developed by scientists as models of changes in total bond energy. Students develop their own mental models for energy changes in chemical reactions that they can express in pictorial models that may look like these. *Source*: M. d'Alessio. Long description of Figure 7.27.

In students' **models [SEP-2]** of chemical reactions, original chemical bonds are broken and new bonds form. Each of these changes affects the distribution of energy within the chemical system, so they must extend their **model [SEP-2]** to include these energy flows. **Energy conservation [CCC-5]** in chemical processes is, however, an abstract concept and must be discussed and developed with care. Students **conduct investigations [SEP-3]** to collect and **analyze data [SEP-4]** (both quantitative and descriptive observations) to discover that some reactions appear to release energy to their environment while others absorb it. In a more detailed **model [SEP-2]** of the energy flow, however, all chemical reactions both absorb and release energy, just in differing amounts. Chemical bonds are not tangible objects but actually the name given to a situation where two atoms are attracted together by electric forces. Chemical reactions involve separating two atoms (requiring work to overcome their attraction, just like lifting a heavy load against the force of gravity) and bringing a different combination of the atoms closer together (which releases energy, much like a falling ball converts gravitational potential energy to kinetic energy as it is attracted to the Earth and moves closer to it). Whether or not a chemical reaction gives off energy overall depends on the relative magnitudes of these two energies. Chemists usually refer to the potential energy related to the relative position of two interacting atoms in a chemical bond as the *bond energy*. By comparing the bond energy of the products with the bond energy of the reactants, students can construct mathematical **models [SEP-2]** of the energy in the system and predict whether or not energy will be absorbed or released. When salt dissolves in water, new attractions between water and the sodium and chlorine are weak, so the particles remain relatively far apart (releasing relatively little potential energy). The temperature of water goes down when salt dissolves in it because much energy goes into breaking bonds, but less energy is released when the new attractions form. Another example is the classic set of reactions that comprise photosynthesis and respiration. The complex biochemistry of photosynthetic reactions is not necessary at this stage, but the fact that the formation of biomass from carbon dioxide and water requires energy input is an important understanding that has been stressed in earlier grades. Energy input now can be understood in greater detail given the students' comprehension of the energetics of chemical bonds. The equations in figure 7.28 are the net result of a number of other chemical reactions along the way (the various cycles involving ATP and other intermediate molecules). The reason these other reactions are required is because of the energy required to break bonds of the reactants apart (often called the *activation energy*, which some models in figure 7.27 depict as a temporary increase in energy during the chemical reaction). The intermediate stages involve certain proteins encoded by deoxyribonucleic acid (DNA) to re-orient the molecules and reduce the activation energy.

Figure 7.28. Developmental Progression of Models of Energy in Chemical Reactions



Students can revise their models and make them more detailed over time. In the middle grades, students use simplified equations for photosynthesis and aerobic respiration as a model of energy in chemical reactions (left: note that middle grades students are not assessed on balancing chemical equations). An introductory high school model of energy changes during these chemical reactions includes details about bonding energy (middle). A more advanced model that integrates core ideas from life science shows a series of intermediate chemical reactions inside cells each with a smaller activation energy (right). *Source*: M. d'Alessio
Long description of Figure 7.28.

Chemistry in the Earth System Snapshot 7.7: Chemical Energetics

Both the CA NGSS and the California Common Core State Standards for Mathematics (CA CCSSM) include the practice of **developing and using models [SEP-2]**. CA CCSS Math Practice Standard 4 (MP.4) states that high school students should be able "to identify important quantities in a practical situation and map their relationships using such tools as diagrams, two-way tables, graphs, flowcharts and formulas." Having taught for a number of years, Mr. S realized that his chemistry students often memorized diagrams and charts presented in the textbook without being able to apply these models to solving problems or **explaining [SEP-6]** the complex phenomena that they represent.

Anchoring phenomenon: Hot and cold packs look identical on the outside but use different ingredients to "spontaneously" change their temperature warmer or cooler.

Mr. S developed a two-day lesson about modeling the energy in chemical bonds (HS-PS1-4) as part of a larger instructional segment on chemical reactions. At the beginning of class, Mr. S distributed reusable hot and cold packs used to treat sports injuries and instructed his students to flex the bags, feel the change in temperature, measure the temperature change using infrared thermometers obtained from the local building supply store, and record these changes in a collaborative online database. Despite variations in individual recordings among classmates, students noticed similar **patterns [CCC-1]** in the temperature gains or losses for the hot and cold packs.

California Common Core State Standards for English Language Arts/Literacy in History/Social Studies, Science, and Technical Subjects (CA CCSS for ELA/Literacy) standard L.11–12.4b requires students "to apply knowledge of Greek, Latin, and Anglo-Saxon roots and affixes to draw inferences concerning the meaning of scientific and mathematical terminology." Mr. H. wrote the words *endothermic* and *exothermic* on the board and asked students to enter as many words as they know or can find that use the roots: *end-*, *ex-* and *therm-* into an online form. Within a couple of minutes, the collaborative cloud-based list had grown to several dozen words, including *exit*, *extinct*, *exotic*, *exoskeleton*, *exocrine*, *extraterrestrial*, *endemic*, *endocrine*, *endosperm*, *thermometer*, *thermistor*, *thermophilic*, and *thermoregulation*. Mr. S then prompted his students to predict the meaning of these roots based upon the meanings shared by the words that contain them. Mr. S monitored their predictions as they entered them in an online input form and called upon students whose digital responses demonstrated understanding and who had not shared with the class recently. He asked these students to explain the meanings of these roots and predict the meanings of the words *endothermic* and *exothermic*. After clarifying that *endothermic* means absorbing heat, while *exothermic* means releasing heat, Mr. S

Chemistry in the Earth System Snapshot 7.7: Chemical Energetics

asked students to identify the hot and cold pack reactions as being either endothermic or exothermic, and he once again assessed their responses from the online form.

Confident that his students had an intuitive understanding of exothermic and endothermic reactions as well as the vocabulary to describe these reactions, Mr. S projected a slide comparing several different annotated graphs (figure 7.27) and said, “Different people drew these diagrams to describe chemical reactions. What **patterns [CCC-1]** do you observe? Submit your thoughts to our online form.” Scanning student responses, Mr. S formatively assessed the ability of his class to observe salient patterns, and noticed that the majority had noted that multiple drawings included one or more of the following features: two axes, time/progress axis, energy/enthalpy axis, changing molecular models, changing chemical formulas, changing energy values, and/or arrows indicating that energy is absorbed or released. Mr. S then selected Isabella, a student who had not had an opportunity to share in the last few days, to explain her observations. Isabella was confident that she has something significant to share because she knew that Mr. S pre-screened student responses in the cloud and only called on students who had demonstrated that they had something worth sharing. Isabella commented on the similarities and differences between the diagrams and explained that the model in the upper left might represent the heat pack while one next to it might represent the cold pack. Mr. S asked her to **provide evidence to support her argument [SEP-7]**, which she did. Mr. S then asked other students to share their observations and concluded by emphasizing that there are multiple ways to model or represent natural phenomena, and that each has its strengths and weaknesses. He then emphasized that some models are better at explaining or predicting phenomena than others, and that we should strive to improve our **models [SEP-2]** of the natural world to better explain the complex processes they represent.

Mr. S emphasized the idea that a chemical reaction affects the energy change of a system and can be **modeled [SEP-2]** with molecular-level drawings and diagrams of reactions, graphs showing the relative energies of reactants and products, and representations showing energy is conserved (also represented in figure 7.27). After explaining each model, Mr. S assigned as homework an online quiz that assessed student understanding of each type of model.

Chemistry in the Earth System Snapshot 7.7: Chemical Energetics

Investigative phenomenon: Different chemical reactions produce different temperature changes.

On day 2, students planned and **conducted investigations [SEP-3]** using probes and computer probeware to continuously monitor the temperature change accompanying the following reactions:

1. $CaO(s) + H_2O(l) \rightarrow Ca(OH)_2(s)$
   (lime + water)
2. $NH_4NO_3(s) + H_2O\ (l) \rightarrow NH_4^+(aq) + NO_3^-(aq)$
   (ionization of ammonium nitrate, a fertilizer)
3. $HCl(dilute) + NaOH(dilute) \rightarrow H_2O + NaCl$ (neutralization)
4. $NaCl + H_2O \rightarrow Na^+(aq) + Cl^-(aq)$ (dissolving table salt)
5. $CaCl_2 + H_2O \rightarrow Ca^+(aq) + 2Cl^-(aq)$ (de-icing roads)
6. $NaHCO_3(s) + HCl(aq) \rightarrow H_2O(l) + CO_2(g) + NaCl(aq)$ (neutralization)
7. $CH_3COOH(aq) + NaHCO_3(s) \rightarrow CH_3COONa(aq) + H_2O(l) + CO_2(g)$
   (baking soda and vinegar)
8. $C_{12}H_{22}O_{11} + H_2O$ (in 0.5M HCl) $\rightarrow C_6H_{12}O_6$ (glucose) $+ C_6H_{12}O_6$
   (fructose) (decomposing table sugar)
9. $KCl + H_2O \rightarrow K^+(aq) + Cl^-(aq)$ (dissolving potassium chloride)
10. $NaCl + CH_3COOH(aq) \rightarrow Na^+(aq) + CH_3COO^- + HCl$
    (preparing HCl to clean tarnished metals)

Students took screen captures of the temperature plots, classified each reaction as endothermic or exothermic, and represented it using two or more of the model types shown in figure 7.27, or an additional model type that they developed on their own. When writing their lab reports, students applied scientific principles and evidence to **construct explanations [SEP-6]** for the thermal **changes [CCC-7]** that they had observed in each reaction.

Mathematical Models of Chemical Energy

Students observed differences in the relative strength of different types of bonds and attractions. Would they expect these differences to correlate to different amounts of energy stored in these bonds? Students can **analyze data [SEP-4]** about binding energy from published data tables or from their own investigations to look for **patterns [CCC-1]**.

The assessment boundary of HS-PS1-4 states that students will not be assessed within the CA NGSS on calculations of total bond energy in chemical reactions. Even though students' models of bond energy are only required to be conceptual, these calculations can provide more advanced students opportunities to apply and improve their stoichiometry skills. For example, students can predict the temperature change when they react a certain mass of reactants.

IS5 Chemistry in the Earth System Instructional Segment 5: Chemistry of Climate Change

In this instructional segment students apply their understanding of chemical reactions to global climate. Many of the key issues illustrated build on concepts related to thermodynamics and **energy [CCC-5]** balances within systems (from IS2) and the products of chemical reactions (from IS4). This instructional segment focuses on the natural cycle of carbon and human impacts on it (EP&Cs III, IV). Since the carbon cycle is intricately linked to all life on Earth, this instructional segment integrates with life science units in which students explore the impact of this physical science concept on the Earth system.

CHEMISTRY IN THE EARTH SYSTEM INSTRUCTIONAL SEGMENT 5: CHEMISTRY OF CLIMATE CHANGE

Guiding Questions

- What regulates weather and climate?
- What effects are humans having on the climate?

Performance Expectations

Students who demonstrate understanding can do the following:

HS-ESS2-2. Analyze geoscience data to make the claim that one change to Earth's surface can create feedbacks that cause changes to other Earth systems. [Clarification Statement: Examples should include climate feedbacks, such as how an increase in greenhouse gases causes a rise in global temperatures that melts glacial ice, which reduces the amount of sunlight reflected from Earth's surface, increasing surface temperatures and further reducing the amount of ice. Examples could also be taken from other system interactions, such as how the loss of ground vegetation causes an increase in water runoff and soil erosion; how dammed rivers increase groundwater recharge, decrease sediment transport, and increase coastal erosion; or how the loss of wetlands causes a decrease in local humidity that further reduces the wetland extent.]

CHEMISTRY IN THE EARTH SYSTEM INSTRUCTIONAL SEGMENT 5: CHEMISTRY OF CLIMATE CHANGE

HS-ESS2-4. Use a model to describe how variations in the flow of energy into and out of Earth's systems result in changes in climate. [Clarification Statement: Examples of the causes of climate change differ by timescale, over 1-10 years: large volcanic eruption, ocean circulation; 10-100s of years: changes in human activity, ocean circulation, solar output; 10-100s of thousands of years: changes to Earth's orbit and the orientation of its axis; and 10-100s of millions of years: long-term changes in atmospheric composition.] *[Assessment Boundary: Assessment of the results of changes in climate is limited to changes in surface temperatures, precipitation patterns, glacial ice volumes, sea levels, and biosphere distribution.]*

HS-ESS2-6. Develop a quantitative model to describe the cycling of carbon among the hydrosphere, atmosphere, geosphere, and biosphere. [Clarification Statement: The carbon cycle is a property of the Earth system that arises from interactions among the hydrosphere, atmosphere, geosphere, and biosphere. Emphasis is on modeling biogeochemical cycles that include the cycling of carbon through the ocean, atmosphere, soil, and biosphere (including humans), providing the foundation for living organisms.]

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-ESS3-5. Analyze geoscience data and the results from global climate models to make an evidence-based forecast of the current rate of global or regional climate change and associated future impacts to Earth systems. [Clarification Statement: Examples of evidence, for both data and climate model outputs, are for climate changes (such as precipitation and temperature) and their associated impacts (such as on sea level, glacial ice volumes, or atmosphere and ocean composition).] *[Assessment Boundary: Assessment is limited to one example of a climate change and its associated impacts.]*

HS-ESS3-6. Use a computational representation to illustrate the relationships among Earth systems and how those relationships are being modified due to human activity.* [Clarification Statement: Examples of Earth systems to be considered are the hydrosphere, atmosphere, cryosphere, geosphere, and/or biosphere. An example of the far-reaching impacts from a human activity is how an increase in atmospheric carbon dioxide results in an increase in photosynthetic biomass on land and an increase in ocean acidification, with resulting impacts on sea organism health and marine populations.] *[Assessment Boundary: Assessment does not include running computational representations but is limited to using the published results of scientific computational models.]*

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

CHEMISTRY IN THE EARTH SYSTEM INSTRUCTIONAL SEGMENT 5: CHEMISTRY OF CLIMATE CHANGE

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-2] Developing and Using Models [SEP-4] Analyzing and Interpreting Data [SEP-5] Using Mathematics and Computational Thinking [SEP-7] Engaging in Argument from Evidence	ESS1.B: Earth and the Solar System ESS2.A: Earth Materials and Systems ESS2.D: Weather and Climate PS3.B: Conservation of Energy and Energy Transfer PS3.D: Energy and Chemical Processes in Everyday Life PS4.B: Electromagnetic Radiation ESS3.A: Natural Resources ESS3.D: Global Climate Change	[CCC-2] Cause and Effect: Mechanism and Explanation [CCC-4] Systems and System Models [CCC-5] Energy and Matter: Flows, Cycles, and Conservation [CCC-7] Stability and Change

Highlighted California Environmental Principles and Concepts:

Principle III Natural systems proceed through cycles that humans depend upon, benefit from and can alter.

Principle V Decisions affecting resources and natural systems are complex and involve many factors.

CA CCSS Math Connections: N-Q.1; F-LE.1b, c; S-ID.6, 7; MP. 1, MP. 2, MP. 3, MP.4

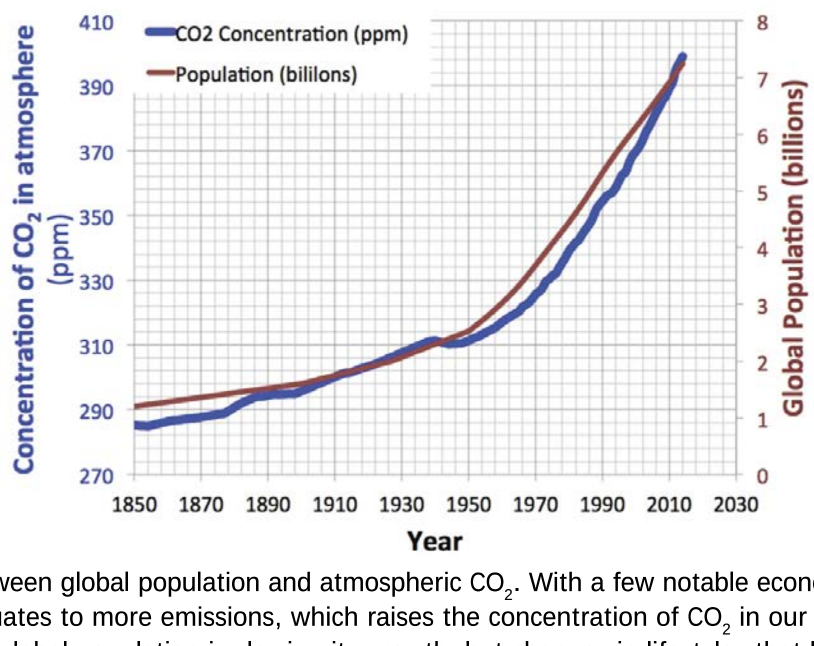
CA CCSS for ELA/Literacy Connections: SL.9–10.1c–d, SL.11–12.1c–d; WHST.9–10.4, 6, 9, 10; RST.9–10.1, 7, 9

CA ELD Connections: ELD.PI.9–10.1, 2, 3, 6a–b, 11a; ELD.PII.9–10.1

Students revisit the introductory activity in IS1 on combustion through the lens of their new mental **models [SEP-2]**. Students likely have prior knowledge that combustion requires oxygen and gives off **energy [CCC-5]** in the same way as aerobic respiration. In fact, looking at the initial and final products, combustion reactions are identical to the aerobic reaction shown in figure 7.28. The energy obtained by chemical reactions inside our bodies is the same as the energy released in the combustion reaction in food calorimetry, which is why we can burn food to figure out how much energy it will give us. They can also understand why a match or lighter is needed to provide the initial activation energy to start the chemical reaction. Students also likely have prior knowledge that they exhale CO_2, and by feeling the moisture in their breath, they can realize that they also exhale water in a gaseous form. Despite the fact that they cannot see either of these gases, both have mass. When people exhale, they are losing weight (and in fact, vigorous exercise that makes them exhale more will indeed allow them to lose more weight). In the food calorimetry experiment, students measured the mass of the food at the beginning and compared it to the remaining mass and noticed that some of the mass disappeared. They can now revise their model to show that it was released as hot CO_2 and H_2O gas. Its mass flowed out of the smaller **system [CCC-4]** of their laboratory investigation and into the air of the room around it (much like mass flowed into the system to provide the oxygen for the reactants). If they considered the entire room as their **system [CCC-4]** and were able to measure its mass, they would have seen that it remained unchanged during the experiment.

Combustion can occur in a range of materials besides food. Combustion that involves molecules made entirely of carbon, hydrogen, and oxygen (hydrocarbons) will always release the same reaction products (albeit in different ratios; see IS5). Most of the fuels used in everyday life are hydrocarbons, including logs of firewood, natural gas on stovetops, and gasoline in cars. All of these hydrocarbons produce carbon dioxide as they provide the energy people use every day. In fact, as more and more people inhabit the planet, more carbon dioxide is being emitted into the atmosphere every day, where it accumulates (figure 7.29).

Figure 7.29. Relationship Between Global Population and Atmospheric CO_2



Relationship between global population and atmospheric CO_2. With a few notable economic slowdowns, more people equates to more emissions, which raises the concentration of CO_2 in our atmosphere. In recent years, global population is slowing its growth, but changes in lifestyles that burn more hydrocarbons for energy are causing emissions to continue to grow. *Source*: M. d'Alessio using data from NASA n.d.; National Oceanic and Atmospheric Administration 2016a; United Nations, Department of Economic and Social Affairs, Population Division 2015; United States Census Bureau 2016
Long description of Figure 7.29.

The carbon dioxide produced by combustion plays a crucial role in regulating Earth's climate system (EP&C IV, see also EEI curriculum unit on the *Greenhouse Effect on Natural Systems* at https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link24). In this instructional segment, students apply their understandings of conservation of **energy [CCC-5]** and heat flow (from IS2) and interactions between **energy and matter [CCC-5]** (from the High School Three-Course Model Physics of the Universe course) to understand this role. The topic of global climate change offers an excellent opportunity to explore the concept of planet Earth as a **system [CCC-4]** (ESS2.A), and to apply science and engineering practices to a very important and highly visible societal issue (HS-ETS1-1). While the details of global climate change can be very complex and technical, the underlying science has been known for a long time and is quite understandable. The main ideas relate to

- the **flows of energy [CCC-5]** into, within, and out of the Earth system;
- Earth's **cycles of matter [CCC-5]**, especially the carbon cycle;
- the **effects [CCC-2]** of human activities, especially the combustion of fossil fuels.

Opportunities for ELA/ELD Connections

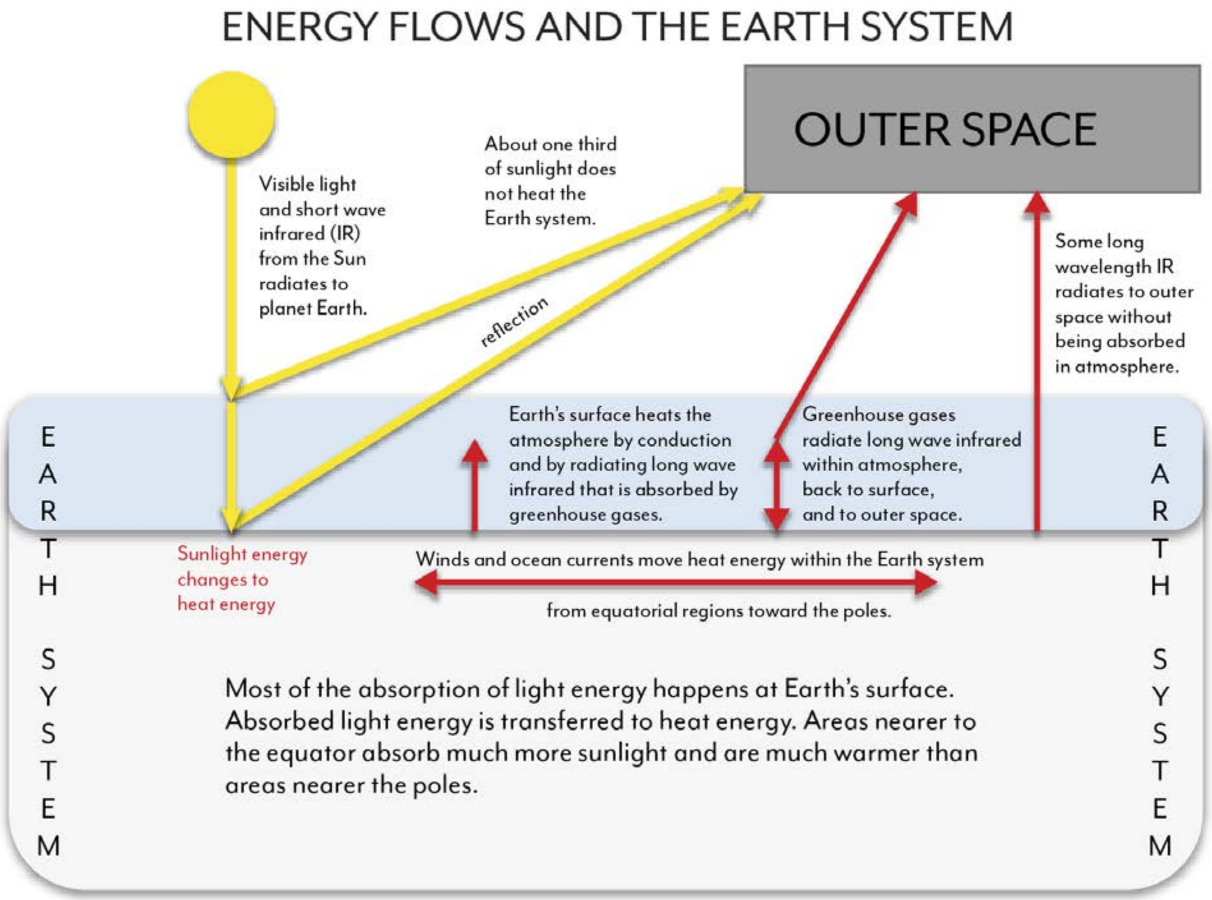
Students select and read a current article, from a scientific site or publication, about an example of how a change to the Earth's surface can cause changes to the global climate. The teacher may want to focus articles on topics included in IS5, such as greenhouse gases, deforestation, damming rivers, loss of wetlands, or burning fossil fuels. Encourage students to develop and organize their notes based on the organization of the topic and subtopics in the articles (cause/effect, Cornell notes, or summarizing key ideas using critical vocabulary) or a reading annotation system (highlighting main ideas or claims, underlining supporting evidence, circling critical vocabulary, and placing a question mark by unknown content).

CA CCSS for ELA/Literacy Standards: RST.9–12.2, 4, 5
CA ELD Standards: ELD.PI. 9–12.6

The performance expectations in this instructional segment build on significant work on disciplinary core ideas related to weather and climate (ESS2.D) in the middle grades standards in which students learned that ocean and atmospheric currents are the equivalent of Earth's circulation system, transferring heat from the warm equator towards the cooler poles and bringing the planet closer to thermal balance (MS-ESS3-4, now understood more deeply through HS-PS3-4). Students have also learned about the role that moving air masses play in determining short-term weather (MS-ESS2-5). They have been introduced to climate change and that global average temperatures have risen in the last century and have investigated possible causes (MS-ESS2-6). In this instructional segment they must delve into a more sophisticated understanding of Earth's **energy [CCC-5]** balance and its relationship to the global carbon **cycle [CCC-5]**.

The crosscutting concept of **systems [CCC-4]** is crucial to understanding Earth's climate. When scientists think about a system, they need to consider the **energy and matter [CCC-5]** that flow into or out of the system, as well as the inner workings of the system. In some systems, it is hard to decide where to draw the boundaries between what is considered inside the system and what is considered outside (such as the example of the missing mass in the food calorimetry investigation that was not really missing if we considered the room as a system). Earth's climate, however, does not present such a challenge if we consider the entire planet Earth as a system. Earth is somewhat isolated out in space, with relatively little matter entering or leaving the planet. **Energy [CCC-5]**, however, flows into and out of the Earth (figure 7.30).

Figure 7.30. Energy Flows in the Earth System



Energy flows in the Earth system, an illustration of a systems model. Diagram by Dr. Art Sussman, courtesy of WestEd.
Long description of Figure 7.30.

Students can make a conceptual model of Earth's energy budget using an analogy of the line for a ride at an amusement park. The constant stream of eager visitors arriving at the end of the line represents solar radiation. As visitors get on the ride at the front of the line, they act like energy radiating out into space. Earth's global average temperature measures the amount of heat stored internally in Earth's system and so it is like the number of people waiting in line at any given time. The line will remain the same length if people get on the ride as quickly as new people arrive at the end of the line. Earth's temperature will remain **stable [CCC-7]** as long as the energy input and output remain unchanged.

Earth's **energy [CCC-5]** input comes almost entirely from the Sun. While there is a small amount of radioactive decay within Earth's interior that generates heat, the flow of solar energy to Earth's surface is about 4,000 times greater than the flow of energy from

Earth's interior to its surface. Relatively small changes in the solar input can result in an Ice Age or the melting of all of Earth's ice, much like the sudden arrival of a large group at an amusement ride can cause the line to quickly grow longer. The line will stabilize at this new length (without continuing to grow) as long as the influx of people returns back to its original rate. Planets can do the same thing, maintaining their temperature at a new value after a temporary disturbance.

Most of the sunlight that reaches Earth is absorbed and transformed to thermal **energy [CCC-5]**. If there were no atmosphere to hold that energy, it would radiate right back into space as infrared radiation (like an unpopular amusement park ride where people get on as soon as they arrive because there is no line). Gases in the atmosphere, such as CO_2, absorb infrared energy heading into space and **cause [CCC-2]** it to remain within the Earth system for a longer period of time. Because these gases have the same effect as a greenhouse where heat is trapped inside the system, gases like CO_2 are referred to as greenhouse gases. Calculations by scientists show that if Earth had no greenhouse gases, its surface temperature would be near 0°F (or -18°C) instead of its current value of a much warmer 59°F (15°C). The energy coming into the Earth is still balanced almost exactly by what is leaving the planet but there is enough heat trapped in the system to allow life to thrive (like the amusement park ride whose line is always the same length).

By increasing the amount of greenhouse gases in the atmosphere, human activities are increasing the greenhouse effect and warming Earth's climate. In a given year, less energy leaves Earth than arrives. It's like one of the seatbelts breaks on the amusement park ride and fewer people are able to get on the ride at a time. All of a sudden, the line gets longer and longer as new people arrive because people are not able to leave the line as quickly at the front. At the amusement park, this might lead to impatient children. On Earth, the imbalance in energy flows leads to an overall rise in average temperature.

Chemistry in the Earth System Snapshot 7.8: Structure and Function in Greenhouse Gases

Anchoring phenomenon: A methane leak from a natural gas storage facility is considered by some to be the largest climate disaster in US history.

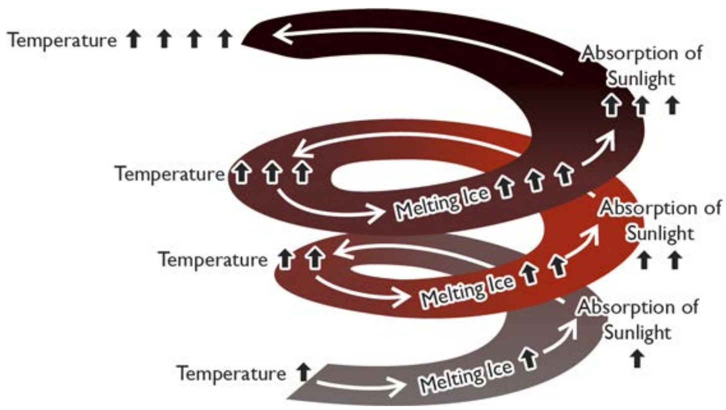
Motivated by the recent news story about a major methane leak in California, Mr. P's students were **asking questions [SEP-1]** about what other gases can trap infrared energy. Mr. P wanted his honors chemistry students to develop **models [SEP-2]** of how greenhouse gases absorb infrared energy. They began with a basic computer simulation (see PhET, *The Greenhouse Effect* at https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link25) showing how molecules can absorb energy as the atoms in the bond vibrate towards and away from one another.

Investigative phenomenon: Some molecules absorb infrared energy more than other molecules.

The simulator demonstrates the effects of different molecules with different bonds and different **structures [CCC-6]**. Mr. P provided information about molecular structures and the qualitative principles about how repulsion between valence electrons helps control the structure of molecules. These structures have a strong influence on the vibrational energy molecules can absorb. Mr. P had students use evidence from the simulator to **construct an argument [SEP-7]** about why methane, water vapor, and carbon dioxide are strong greenhouse gases while oxygen and nitrogen are not. This phenomenon was a more advanced demonstration of how atomic-scale properties can influence bulk behavior (HS-PS1-3).

Amusement parks and planets are **systems [CCC-4]** with complicated inner workings. When lines for one ride at an amusement park get too long, visitors inside the park may respond by going to another ride or park operators may add additional workers or cars to help move people through more quickly. Similar changes happen in Earth's system of systems. While the greenhouse effect seems like a simple **cause and effect [CCC-2]** relationship viewed from outside the system, interactions *within* the system can often give rise to more complicated chains of cause and effect referred to as *feedbacks*. Climate scientists are particularly concerned about feedback effects that could increase the amount and rate of global climate change. One example is that global warming is clearly reducing the amount of ice on our planet (figure 7.31). Glaciers around the world are shrinking in size and even disappearing. The amount of ice covering the ocean in summer and fall is also shrinking. As the ice melts, the surface beneath it is darker in color and absorbs more incoming sunlight. More absorption causes more heating, and this heating causes even more absorption of sunlight. This kind of feedback loop amplifies or reinforces the change, and the distinction between **cause and effect [CCC-2]** begins to blur as each effect causes more change. The clarification statements in the CA NGSS and many scientists use the term *positive feedback*, but this term should be replaced because it leads to confusion—many *reinforcing feedbacks* have very negative outcomes.

Figure 7.31. A Reinforcing Feedback in Earth's Climate

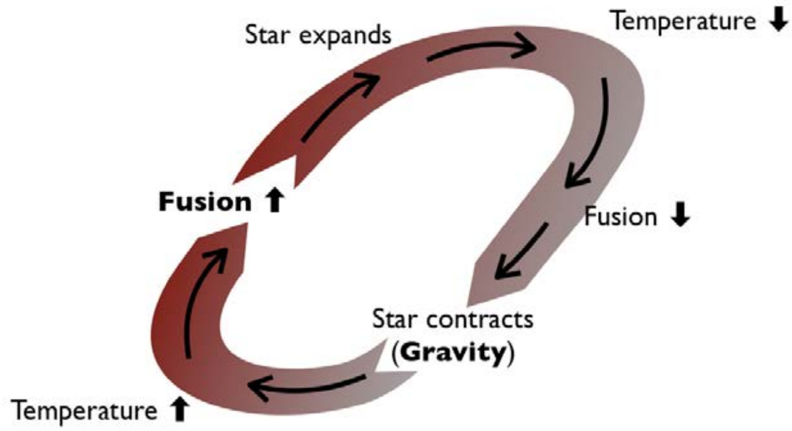


A reinforcing feedback in Earth's climate system. As the planet warms, more ice will melt, which will expose darker ground surfaces that absorb more sunlight, which will in turn make temperatures rise even more. Diagram by M. d'Alessio and A. Sussman.
Long description of Figure 7.31.

A *counterbalancing feedback loop* reduces the amount of change (figure 7.32). For example, warmer temperatures cause more water to evaporate, which enables more clouds to form. Since clouds reflect sunlight back into space, more clouds cause more incoming solar energy to be reflected before it has a chance to be absorbed by the planet. This causes decreasing global temperatures. More warming could cause more cloud formation and reflection, which would then lead to less warming again.[9] These changes are opposite and can balance each other out.

9. Even though this example describes a counterbalancing feedback involving clouds, clouds are also involved in a reinforcing feedback where they trap more heat, causing more evaporation, and more clouds that trap more heat. Both of these mechanisms occur on Earth. The question researchers are currently trying to answer is, "Which feedback loop is more powerful, reinforcing or counterbalancing?" **Cause and effect [CCC-2]** gets very complicated in the Earth system.

Figure 7.32. A Counterbalancing Feedback in Earth's Climate System



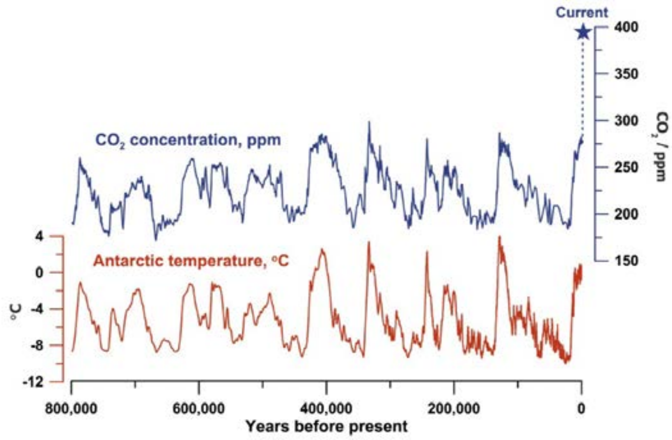
Temperature changes cause changes to the number of clouds because of evaporation. Clouds, in turn, reflect light. Diagram by M. d'Alessio and A. Sussman.
Long description of Figure 7.32.

Scientists discover these complicated interactions between different components of Earth's **systems [CCC-4]** by looking for trends and **patterns [CCC-1]** in climate data. The CA NGSS have a strong emphasis on data analysis, especially in the sections related to weather and climate:

> An important aspect of Earth and space science involves making inferences about events in Earth's history based on a data record that is increasingly incomplete that farther you go back in time … . Students can understand the analysis and interpretation of different kinds of geoscience data. Allow students to construct explanations for the many factors that drive climate change over a wide range of time scales. (NGSS Lead States 2013d)

Some of the strongest **evidence [SEP-7]** about our changing climate comes from ice-core records (figure 7.33). As snow accumulates over time in glaciers around the globe, it traps both the water that recently fell as precipitation and air bubbles. These air bubbles act as tiny time capsules that allow scientists to study actual samples of the ancient atmosphere. Since snow and ice build up seasonally, the timing of each layer of ice and its trapped air bubbles can be counted like tree rings. Scientists make detailed chemical analyses of the water to reconstruct the global average temperature. Details of how this isotopic analysis provides a proxy for global temperature is beyond the scope of high school performance expectations, but is a fascinating example of physics, chemistry, and earth science working together.

Figure 7.33. Temperature and Carbon Dioxide Over the Last 800,000 Years



Source: The Royal Society 2014
Long description of Figure 7.33.

Chemistry in the Earth System Snapshot 7.9: Trends and Patterns in Modern Atmospheric CO_2 Levels

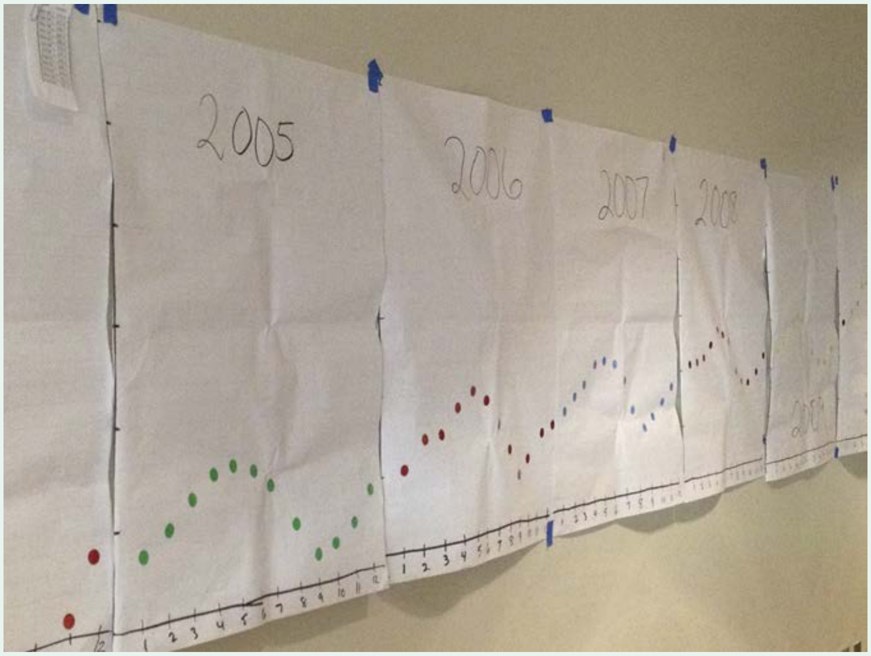
Investigative phenomenon: Atmospheric CO_2 consistently rises and falls with the seasons but also is consistently rising from year to year.

Ms. R wanted the students to get a sense for how much CO_2 there was and how it has changed over time. She introduced the units of parts per million (ppm), relating it to the familiar concept of percent (parts per hundred). She also used her city, which had almost a million people in it, as an analogy in which the school's population of 2,700 equates to 2,700 ppm of the city. CO_2 molecules in the atmosphere are even rarer than that, at about 400 ppm. Ms. R distributed a poster-size piece of graph paper to each team, along with sticker dots and a table showing one year's worth of atmospheric CO_2 measurements recorded each month at the top of Mauna Loa in Hawaii (see NOAA, Trends in Atmospheric CO_2 at https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link26). Each team placed stickers to plot data from a different year, but all graph papers had identical axes with identical scales. She asked students to identify trends and **patterns [CCC-1]** they saw in their one year of data and almost every group indicated that the graph went up and down once over the course of the year, with the peak value sometime in the middle of the year. Students associated the changes with the seasons since they repeat once a year. The pattern of fluctuating CO_2 relates to the growth of vegetation; since there is more vegetated land area in the northern hemisphere, the consumption of CO_2 by plants varies as seasons shift from the productive summer months in the northern hemisphere to summer in the southern hemisphere.

Chemistry in the Earth System Snapshot 7.9: Trends and Patterns in Modern Atmospheric CO_2 Levels

The class taped their graphs side by side to the wall in sequence so that they create one long time-series graph. Each class period was assigned additional data from different years and by the end of the school day, her classes had filled the entire length of the hallway with 35 years of data (figure 7.34). She showed an interactive visualization of global CO_2 data (see NOAA, History of atmospheric carbon dioxide from 800,000 years ago until January, 2014 at https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link27) so that students could observe the trend using a more dynamic visualization, and she asked students to **evaluate [SEP-8]** the benefits of using each format. Ms. R began the next class period having students walk along the entire graph. She asked each team of students to **analyze [SEP-4]** the past data and draw a graph predicting the next five years, extrapolating both the long-term trend of increasing CO_2 and the annual variation. She had them calculate the year in which atmospheric CO_2 would reach 540 ppm (approximately double the pre-industrial CO_2 levels), assuming that current trends continue. When students compared their predictions, she had them discuss assumptions they made about how quickly the CO_2 would increase (some groups assumed a linear increase, while others noticed that the curve seemed to be rising more and more each year). She related back to this discussion when the class researched energy resources.

Figure 7.34. Time Series of CO_2 on a Classroom Wall



Picture by M. d'Alessio
Long description of Figure 7.34.

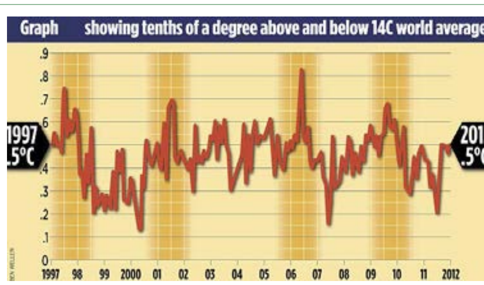
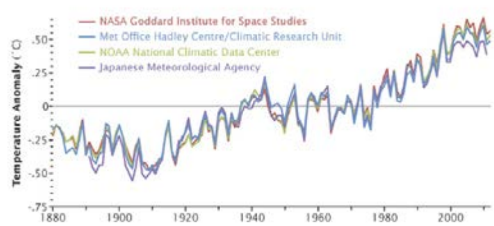
The temperature record from the last half million years reveals some dramatic **patterns [CCC-1]** as temperatures go up and down with a periodicity of about 100,000 years, each low temperature an ice age (National Oceanic and Atmospheric Administration, National Climatic Data Center 2008). When students examine such data, they should be able to **ask questions [SEP-1]** about which parts of the climate **system [CCC-4]** might have **caused [CCC-2]** these changes. If students compare temperature reconstructions with reconstructions of the amount of **energy [CCC-5]** received from the Sun (which varies as the Earth's orbit wobbles and the Sun's energy output changes cyclically over time), they will discover that the data sets have a similar **pattern [CCC-1]**: many warm periods in the ice core data correspond to periods of higher solar energy input (EP&C II). This seems quite reasonable because the Sun's input should influence our temperature. However, there are also time intervals where the Earth was hot that do not correspond to high solar energy. The **pattern [CCC-1]** in the history of the concentration of CO_2 in Earth's atmosphere and temperatures is very similar; the two are highly correlated. This correlation is a key piece of **evidence [SEP-7]** that CO_2 also plays a role in affecting Earth's temperature. In a classroom, this correlation can motivate a discussion of Earth's energy budget and the greenhouse effect.

Chemistry in the Earth System Snapshot 7.10: Letters to the Editor and Evaluating Climate Change Graphs

Anchoring phenomenon: Two news stories about the same scientific research have different headlines and are supported by different graphs of the same data set.

Earlier in the year, Ms. Q had her students read about how to **evaluate [SEP-8]** the scientific arguments made in media sources using a checklist called the Science Toolkit (see UC Museum of Paleontology at https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link28). To begin this unit, she had them read two Internet articles with radically different headlines that each used a graph of global temperature as **evidence [SEP-7]**. Students worked in pairs to evaluate the two articles based on the criteria outlined in the Science Toolkit. Walking around the room, Fernando asked her about the sources: "This article is from NASA, but what is the Weekly Star? Who wrote it?" She encouraged him to do a quick internet search about the newspaper's editorial board. A bit later, Cynthia mentioned that both articles use graphs (figure 7.35), but they look totally different.

Figure 7.35. Two Representations of the Same Data Set by Different Sources

Global warming stopped 16 years ago, reveals Met Office report quietly released ... and here is the chart to prove it	Long-Term Global Warming Trend Continues
	
Weekly Star (fictitious)	NASA's Earth Observatory 2013

Long description of Figure 7.35.

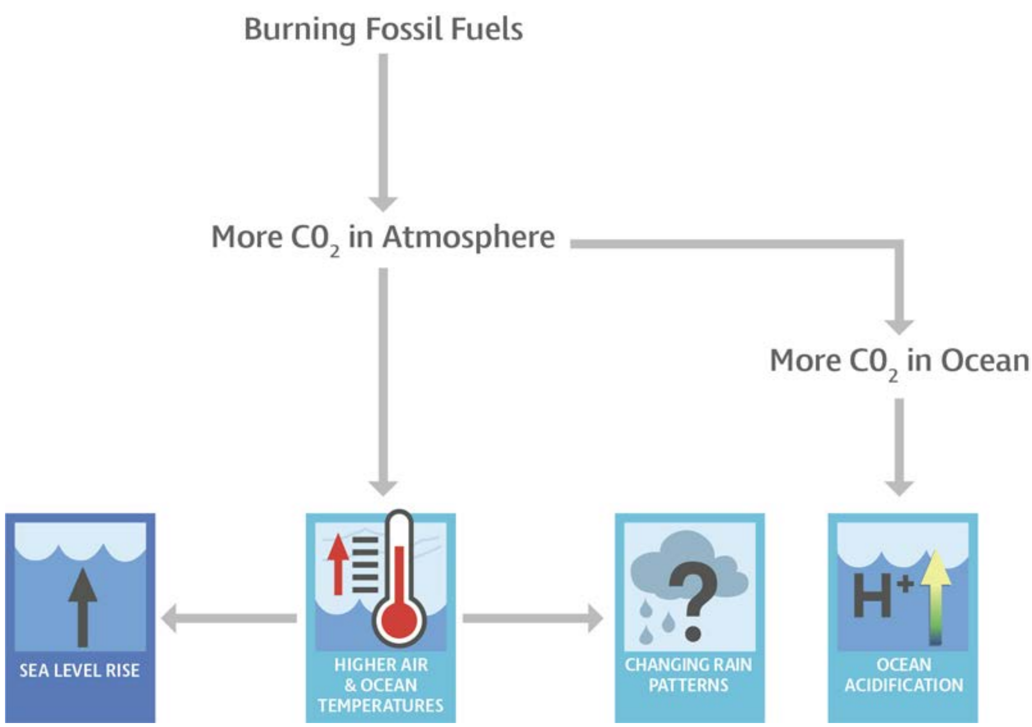
Ms. Q then asked the whole class to discuss the graphs and construct an **argument [SEP-7]** about which graph contained stronger **evidence [SEP-7]**. Ali noticed that one graph included a much longer span of time, "and climate is supposed to be a long-term thing." Jenni said, "This graph has four lines from scientists all over the world that all show the same ups and downs. That shows science is repeatable, and I like that." To conclude the lesson, students wrote letters to the editor in response to the *Weekly Star* article articulating their **argument [SEP-7]**.

In the CA NGSS, students combine their general understanding with **computational thinking [SEP-5]** by using simple computer simulations (see PhET, *The Greenhouse Effect* at http://www.cde.ca.gov/ci/sc/cf/ch7.asp#link29) to model the **flow of energy [CCC-5]** into and out of the Earth and the role that CO_2 and other greenhouse gases play in that process (HS-ESS2-4). Scientists use simulators of Earth's climate called global climate **models [SEP-2]** (GCMs) that are much more detailed and include many other processes and interactions between Earth **systems [CCC-4]**. The assessment boundary of HS-ESS3-6 states that students should not be required to run their own **models [SEP-2]**, though simplified versions of GCMs exist for educational purposes (see Columbia University, Educational Global Climate Modeling Web site at https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link30 and Java Climate Model at http://www.cde.ca.gov/ci/sc/cf/ch7.asp#link31). The advantage of these models is that they enable students to turn on and off different parts of the Earth system to see how they affect the climate. For example, students can compare a model of the Earth without the biosphere to a model that includes the biosphere. As CO_2 increases in the atmosphere, plant growth decreases the impact of global warming (a counterbalancing feedback). Comparing the predictions of a computer model that allows ice to melt with one in which ice is not allowed to melt is another form of **analyzing and interpreting data [SEP-4]** and can help build students' mental **models [SEP-2]** of the climate system. **Models [SEP-2]**, as defined in the CA NGSS, represent a system that allows for predicting outcomes, so the output of a computational model can sometimes be more useful at anticipating the future than simply examining historical data. Ultimately, students need to be able to communicate their mental model by describing specific feedbacks in the Earth system using an argument (HS-ESS2-2). In a classroom, various student teams could examine different elements of an Earth system using teacher-provided results of model runs or creating their own with educational GCMs. They could then compile brief reports to share with their classmates about the **effects [CCC-2]** of these different processes on global climate.

Another crucial observation about Earth's climate is that the concentration of CO_2 and other greenhouse gases in our atmosphere has been growing steadily since the dawn of the industrial era. Students should be able to make connections to the previous instructional segment and know that the vast majority of this increase comes from humans' extraction and combustion of fossil fuels. GCMs allow scientists and students to see how the climate is expected to change as greenhouse gases trap more energy in the atmosphere. Because of the linkages between different components of Earth's **systems [CCC-4]**, these impacts extend to all of Earth's systems. Figure 7.36 shows a few of these linkages. In a classroom, different student groups could **obtain information [SEP-8]** from library and Internet resources to construct a report on the impact predicted for different parts of the world so that the class as a whole could create a product to share with the rest of their school that summarizes the global impacts (HS-ESS3-6).

EEI Curriculum units—*The Life and Times of Carbon* and *The Greenhouse Effect on Natural Systems* (https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link32)—explore human practices that can influence the global carbon cycle and how human activities affect quantities of greenhouse gases. These units can be used in conjunction with this instructional segment to provide materials that examine EP&Cs III and IV.

Figure 7.36. Cause and Effect Chains Illustrate How Human Activities Affect Natural Systems

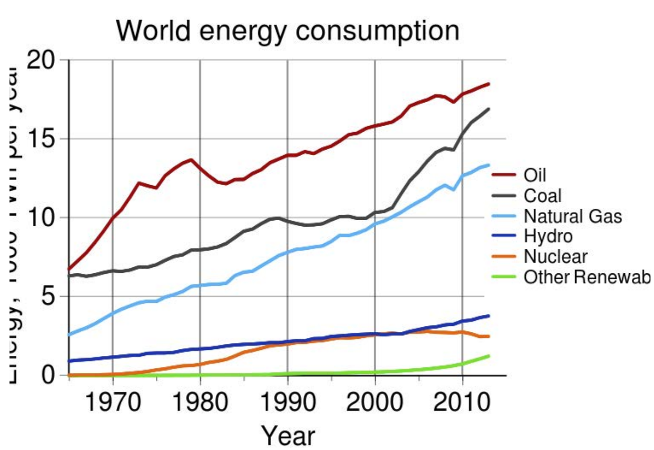


One example of how humans affect the climate, which impacts all parts of Earth's systems. Illustration by Dr. Art Sussman, WestEd, and Lisa Rosenthal, WGBH.
Long description of Figure 7.36.

Engineering Connection: The Chemistry of Global Energy Supplies

Figure 7.37 graphs trends in world energy consumption and illustrates that the three major sources of energy worldwide are fossil fuels (oil, coal, and natural gas). Students can obtain information about the impacts of fossil fuels on natural systems that arise because harnessing the energy from fossil fuels also disrupts global cycles of matter in the Earth system (ESS2.A; EP&C III, IV). Climate change results from rising levels of greenhouse gases (e.g., carbon dioxide, methane, and nitrous oxide). Carbon dioxide is released when fossil fuels react with oxygen during combustion, and students can **obtain information [SEP-8]** about chemical methods of carbon sequestration that are current research topics. Natural gas is primarily methane, which can leak into the atmosphere during production, processing, transport, storage, and distribution. Students can **obtain information [SEP-8]** about cutting-edge technologies to monitor leaks in real time. Acid rain results from nitrogen and sulfur oxides commonly released during combustion of sulfur rich fuels such as coal. Students could **obtain information [SEP-8]** about the chemical technology used to minimize the release of sulfur dioxide. Since these systems were mandated, acid rain has substantially declined in the United States. Smog involves reactions between tailpipe emissions of cars and the air (with sunlight adding some of the energy to break chemical bonds). Students could also **obtain information [SEP-8]** about how improvements to the combustion efficiency of cars have reduced smog. Students should do more than just explain the chemical reactions in each of these processes. They should consider the criteria and constraints about society's need for clean air and clean water along with the need for more energy (HS-ETS1-1; EP&C V). Students should be encouraged to break down the problem into smaller, more manageable problems that can be solved through [chemical] engineering (HS-ETS1-2).

Figure 7.37. What Fuels Provide the World's Energy?



Source: BP 2016

Long description of Figure 7.37.

IS6

Chemistry in the Earth System Instructional Segment 6: The Dynamics of Chemical Reactions and Ocean Acidification

Students will build on their simple model of chemical reactions from IS4 to explore **stability and change [CCC-7]** in chemical **systems [CCC-4]**. They then focus on a chemical system in Earth's ocean where carbon dioxide from the combustion of fossil fuels (as discussed in IS1 and IS5) is having a dramatic impact on ocean life (EP&Cs II, IV).

CHEMISTRY IN THE EARTH SYSTEM INSTRUCTIONAL SEGMENT 6: THE DYNAMICS OF CHEMICAL REACTIONS AND OCEAN ACIDIFICATION

Guiding Questions

- How can you alter chemical equilibrium and reaction rates?
- How can you predict the relative quantities of products in a chemical reaction?

Performance Expectations

Students who demonstrate understanding can do the following:

HS-PS1-5. Apply scientific principles and evidence to provide an explanation about the effects of changing the temperature or concentration of the reacting particles on the rate at which a reaction occurs. [Clarification Statement: Emphasis is on student reasoning that focuses on the number and energy of collisions between molecules.] *[Assessment Boundary: Assessment is limited to simple reactions in which there are only two reactants; evidence from temperature, concentration, and rate data; and qualitative relationships between rate and temperature.]*

HS-PS1-6. Refine the design of a chemical system by specifying a change in conditions that would produce increased amounts of products at equilibrium.* [Clarification Statement: Emphasis is on the application of Le Châtelier's Principle and on refining designs of chemical reaction systems, including descriptions of the connection between changes made at the macroscopic level and what happens at the molecular level. Examples of designs could include different ways to increase product formation including adding reactants or removing products.] *[Assessment Boundary: Assessment is limited to specifying the change in only one variable at a time. Assessment does not include calculating equilibrium constants and concentrations.]*

HS-PS1-7. Use mathematical representations to support the claim that atoms, and therefore mass, are conserved during a chemical reaction. [Clarification Statement: Emphasis is on using mathematical ideas to communicate the proportional relationships between masses of atoms in the reactants and the products, and the translation of these relationships to the macroscopic scale using the mole as the conversion from the atomic to the macroscopic scale. Emphasis is on assessing students' use of mathematical thinking and not on memorization and rote application of problem- solving techniques.] *[Assessment Boundary: Assessment does not include complex chemical reactions.]* (Revisited from IS3 and IS4)

HS-ESS2-2. Analyze geoscience data to make the claim that one change to Earth's surface can create feedbacks that cause changes to other Earth systems. [Clarification Statement: Examples should include climate feedbacks, such as how an increase in greenhouse gases causes a rise in global temperatures that melts glacial ice, which reduces the amount of sunlight reflected

CHEMISTRY IN THE EARTH SYSTEM INSTRUCTIONAL SEGMENT 6: THE DYNAMICS OF CHEMICAL REACTIONS AND OCEAN ACIDIFICATION

from Earth's surface, increasing surface temperatures and further reducing the amount of ice. Examples could also be taken from other system interactions, such as how the loss of ground vegetation causes an increase in water runoff and soil erosion; how dammed rivers increase groundwater recharge, decrease sediment transport, and increase coastal erosion; or how the loss of wetlands causes a decrease in local humidity that further reduces the wetland extent.]

HS-ESS2-6. Develop a quantitative model to describe the cycling of carbon among the hydrosphere, atmosphere, geosphere, and biosphere. [Clarification Statement: **The carbon cycle is a property of the Earth system that arises from interactions among the hydrosphere, atmosphere, geosphere, and biosphere. (CA)** Emphasis is on modeling biogeochemical cycles that include the cycling of carbon through the ocean, atmosphere, soil, and biosphere (including humans), providing the foundation for living organisms.]

*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-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	PS1.B: Chemical Reactions ESS2.A: Earth Materials and Systems ESS2.D: Weather and Climate ETS1.C: Optimizing the Design Solution	[CCC-1] Patterns [CCC-5] Energy and Matter: Flows, Cycles, and Conservation [CCC-7] Stability and Change

Highlighted California Environmental Principles and Concepts:

Principle III Natural systems proceed through cycles that humans depend upon, benefit from and can alter.

Principle V Decisions affecting resources and natural systems are complex and involve many factors.

CA CCSS Math Connections: N-Q.1–3; MP.2, MP.4

CA CCSS for ELA/Literacy Connections: SL.11–12.5; RST.11–12.1, 2

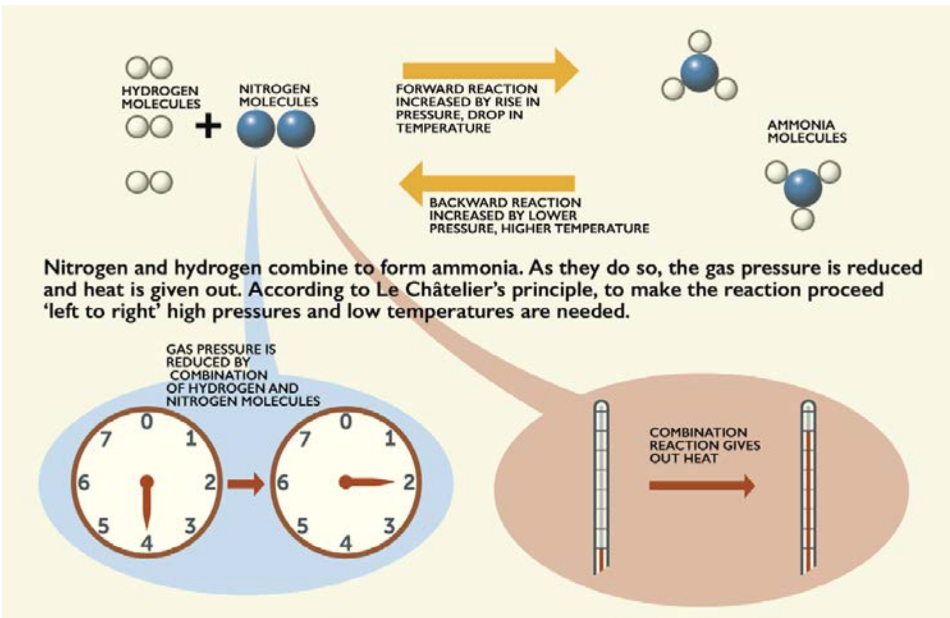
CA ELD Connections: ELD.PI.11–12.1, 5, 6a–b, 9, 10, 11a

Stability [CCC-7] refers to the condition in which certain parameters in a system remain relatively constant, even as other parameters change. Dynamic equilibrium is an example of stability in which reactions in one direction are equal and opposite to those in the reverse direction, so although changes are occurring, the overall system remains stable. Dynamic equilibrium illustrates the principle of stability in an environment undergoing constant change. If, however, the inputs are sufficiently altered, a state of disequilibrium may result, causing significant changes in the outputs.

Once a disruption is made to a **system [CCC-4]**, the speed at which chemical reactions work to re-establish that equilibrium varies depending on a number of factors. Students should be able to gather evidence to **construct** a scientific **explanation [SEP-6]** about what **causes [CCC-2]** these speed variations (HS-PS1-5). In IS4, students **developed a model [SEP-2]** of chemical reactions at the microscopic level that includes atoms colliding with one another and forming new bonds. Students can **investigate [SEP-3]** the response of reaction rates to varying temperatures and concentrations of reactants (both of which make collisions between reactants more likely). For example, students can mix baking soda (sodium hydrogen carbonate, $NaHCO_3$) and vinegar (acetic acid, CH_3COOH) in sealed sandwich bags and gauge the speed and degree of reaction by the rate and amount of CO_2 gas produced as indicated by the swelling of the bag: $NaHCO_3$ (aq) + CH_3COOH (aq) $\rightarrow$ CO_2 (g) + H_2O (l) + CH_3COONa (aq). Students can **investigate [SEP-3]** the role of the quantity of molecular collisions by repeating the activity with differing concentrations of vinegar. They can then **investigate [SEP-3]** the role of temperature by warming or cooling the reactants while keeping their concentrations constant. By observing the swelling of the bags in response to varying temperatures and concentrations, students should discover that those factors that increase the number and **energy [CCC-5]** of molecular collisions (increased concentration and temperature of reactants) result in increased reaction rates. Combining a conceptual **model [SEP-2]** with experimental **evidence [SEP-7]**, students can thus provide reasoned **explanations [SEP-6]** for factors influencing chemical reaction rates.

Once students understand the **effect [CCC-2]** of changing the concentration of reactants and products on reaction rates, they are ready to apply their understanding to novel situations. Performance expectation HS-PS1-6 requires students to “refine the design of a chemical system by specifying a change in conditions that would produce increased amounts of products at equilibrium.” By applying Le Châtelier’s Principle, students can predict ways to increase the amount of product in a chemical reaction. In order to refine the design of a chemical system, students must first be able to measure output and then test the effectiveness of changing the temperature and relative concentrations of reactants and products. For example, gas pressure is reduced and heat is given out when hydrogen and nitrogen combine to form ammonia (figure 7.38). According to Le Châtelier's Principle, the reaction can proceed to produce more ammonia by increasing the pressure and/or by dropping the temperature. Conversely, more ammonia will decompose into hydrogen and nitrogen by lowering the pressure and/or raising the temperature.

Figure 7.38. Le Châtelier's Principle



Students should be able to apply Le Châtelier's Principle to predict ways to increase the amount of product of a chemical reaction. *Source*: The Worlds of David Darling 2015
Long description of Figure 7.38.

As students tackle HS-PS1-6, they must invoke the engineering strategies specified in HS-ETS1-2 in which they are required to **design a solution [SEP-6]** "to a complex real-world problem by breaking it down into smaller, more manageable problems." For example, students might be challenged to increase the amount of precipitated table salt in solution $[NaCl(s) \rightarrow Na^{+}(aq) + Cl^{-}(aq)]$ without adding more salt. By experimenting with the addition of other sodium salts, students may discover that an increase in free sodium ions shifts the reaction in favor of the precipitate. To optimize the production of sodium, students may also experiment with **changes [CCC-7]** in temperature, discovering that decreases in temperature favor the production of precipitate. In doing such **investigations [SEP-3]**, students are applying the engineering skill of optimization as they refine their design to increase productivity. Students can verify their results quantitatively using principles of stoichiometry they developed in IS3 and IS4 (HS-PS1-7).

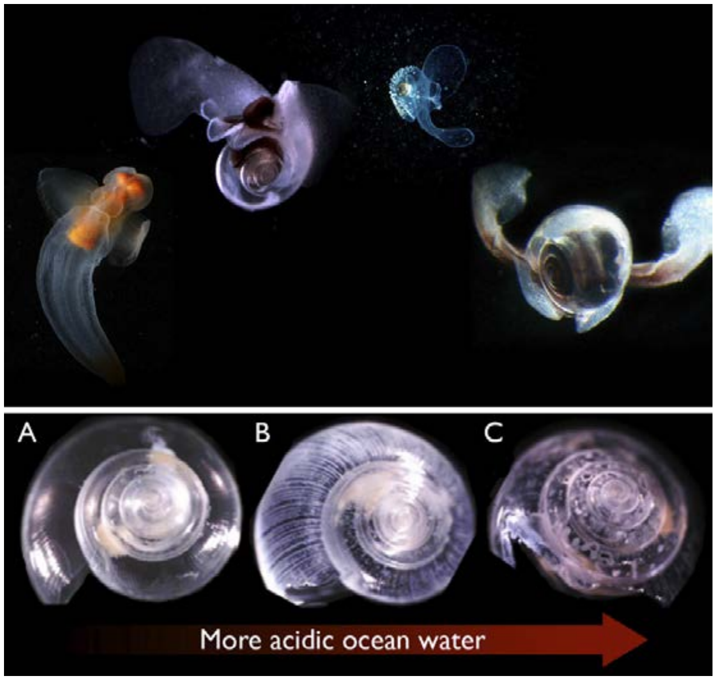
Disrupting Equilibrium in the Ocean

Changes [CCC-7] in the world's oceans bring together all science and engineering disciplines and provide an excellent way to introduce principles of chemical dynamics. Some excellent CA NGSS aligned resources for teaching about ocean chemistry are available, including well-designed curriculum sequences about ocean acidification (Institute for Systems Biology, Ocean Acidification: A Systems Approach to a Global Problem at https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link33). A good activity sequence begins by **obtaining and evaluating information [SEP-8]** in order to **define the problem [SEP-1]** (HS-ETS1-1). In IS5, students saw evidence that human activities emit CO_2 in the atmosphere. While the concentration of CO_2 in our atmosphere is currently 40 percent higher than it was at the start of the Industrial Revolution, it would be even higher if it were not for the ocean. The ocean constantly exchanges CO_2 with the atmosphere so that the two are in equilibrium. As the atmospheric CO_2 goes up, this temporarily disrupts the balance and causes more CO_2 to enter the oceans than leave. Students can examine data showing trends in CO_2 concentrations in the ocean and atmosphere as evidence of a balancing feedback between two of Earth's **systems [CCC-4]** that slows the rate of climate change (HS-ESS2-2). The ocean currently absorbs more than a quarter of the annual emissions of CO_2 from human activities. Students can add this fact to their quantitative **model [SEP-2]** of the carbon cycle (HS-ESS2-6, ties to IS5 of the Living Earth course).

In the ocean, CO_2 molecules have no impact on the atmospheric greenhouse effect. However, the **changes [CCC-7]** in the ocean are significant (EP&Cs II, III, IV). Students can design a simple **investigation [SEP-3]** to generate CO_2 (gas released by a baking soda/vinegar reaction, a combusting candle, or yeast foaming) and explore how it affects the pH using an indicator solution or probe. They find that the ocean becomes more acidic, so this environmental change is termed ocean *acidification*. Students can also investigate the **effect [CCC-2]** that temperature and salinity have on the ability of CO_2 to dissolve into the water (HS-PS1-5).

When CO_2 dissolves in the ocean, the situation is more complex because the CO_2 interacts with living organisms and other inorganic molecules in the seawater. Many rocks in Earth's crust are rich in calcium, so when rivers wash material toward the ocean they bring a rich supply of calcium. While humans and other animals build bones from calcium phosphate, many marine organisms make shells by combining calcium with carbonate, which forms when CO_2 dissolves in seawater. While students may be familiar with some of the larger examples of these organisms like clamshells and coral, some of the most delicate plankton rely on these chemical reactions (figure 7.39). Because they lie at the base of the food chain for many sea creatures, the shells of these delicate organisms are crucial for maintaining ocean ecosystems.

Figure 7.39. Pteropods



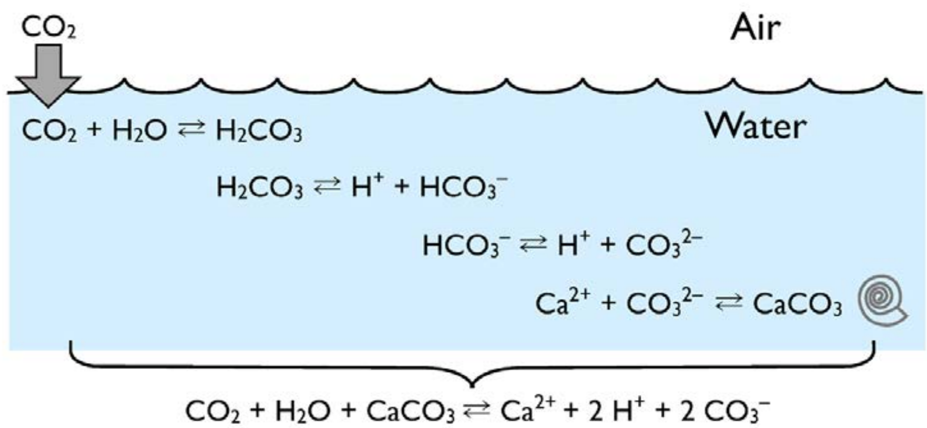
Pteropods are a delicate type of sea creature. The bottom panel shows laboratory experiments demonstrating how their shells dissolve when ocean water is too acidic. *Sources*: National Oceanic and Atmospheric Administration/Department of Commerce, Kevin Raskoff, Hidden Ocean 2005 Expedition: NOAA Office of Ocean Exploration 2005; National Oceanic and Atmospheric Administration/Ocean Explorer 2002; Auster and DeGoursey 2000; Hunt et al. 2010; Busch et al. 2014
Long description of Figure 7.39.

Students apply their **models [SEP-2]** of chemical equilibrium to predict the impacts of changing CO_2 levels in the ocean on these organisms. There are interactions between CO_2, water, and the shells made out of calcium carbonate ($CaCO_3$) represented by a complex **system [CCC-4]** of chemical reactions (figure 7.40). Each reaction is a dynamic equilibrium with products and reactants constantly being created. Simplifying some of the intermediate reactions, the overall system looks like:

$$CO_2 + H_2O + CaCO_3 \rightleftarrows Ca^{2+} + 2\ H^+ + 2\ CO_3^-$$

As students apply their **model [SEP-2]** of equilibrium reactions from Le Châtelier's Principle, they see that as the concentration of CO_2 increases, the **system [CCC-4]** compensates by producing more products on the right side. The addition of H+ ions makes the ocean more acidic. The other important **change [CCC-7]** is that $CaCO_3$ shells dissolve into their constituent ions. Since the beginning of the Industrial Revolution, the concentration of H^+ ions has increased 30 percent, but projections of future CO_2 emissions by humans may lead to increases up to 150 percent. The bottom panels of figure 7.39 reveal the damage that this increased acidity can have on small and delicate organisms. Students can observe these effects themselves by **planning an investigation [SEP-3]** to measure the rate of shell dissolution at different pH levels. Or they can **obtain information [SEP-8]** on the health of coral reefs and coral bleaching, due in part to these pH changes.

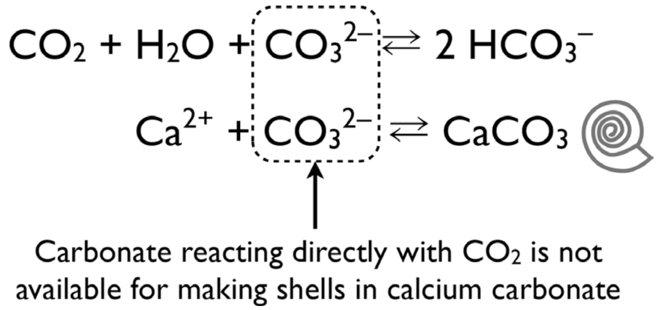
Figure 7.40. Chemical Interactions Between CO_2 and Water



A chain of chemical reactions occurs when CO_2 dissolves in ocean water. All of the reactions are equilibrium. The equation on the bottom summarizes the chain to help illustrate how the system changes with an increase in CO_2. Diagram by M. d'Alessio
Long description of Figure 7.40.

Shell damage is not the only problem marine organisms face as more CO_2 dissolves in the ocean. The chemistry also makes it harder for them to produce shells in the first place. In the engineering task of HS-PS1-6, the clarification statement indicates that the design challenge only needs to involve two reactants, but the mental **model [SEP-2]** of chemical reactions they develop to meet that performance expectation can be applied to understanding this more complex **system [CCC-4]**. Chemical equations are essentially **models [SEP-2]** of these complicated systems, and sometimes different representations of the same **system [CCC-4]** reveal different features. Using a different combination of the intermediate reactions in figure 7.40, the same chemical **system [CCC-4]** can also be represented by figure 7.41.

Figure 7.41. Simplified Equations for Carbonate Shell Chemical Reactions



Source: M. d'Alessio
Long description of Figure 7.41.

The representation in figure 7.41 indicates that both CO_2 and Ca^{2+} want to react with the carbonate ion, so increasing CO_2 decreases the carbonate available for shell production. (Further inspection of figure 7.41 shows that HCO_3^- dissociates to hydrogen and carbonate, and one might think that the carbonate could be used for shell making. While an increase in CO_2 does lead to an increase in carbonate ions, it also leads to an equal increase in hydrogen ions without increasing the concentration of calcium. These hydrogen ions form a tighter, more energetically favorable bond to carbonate than calcium does.) Organisms are less likely to encounter carbonate ions that are not already interacting with hydrogen ions, and have trouble building shells. This will result in slower shell production (leaving the organisms vulnerable for a longer time period) or reliance on additional chemical reactions to liberate the carbonate ions from hydrogen (which would require the organism to invest more **energy [CCC-5]** in shell production, leaving less energy for things like reproduction and evading predators).

CHEMISTRY IN THE EARTH SYSTEM VIGNETTE 7.2: OCEAN ACIDIFICATION, A SYSTEMS-BASED APPROACH TO A GLOBAL PROBLEM

Performance Expectations

Students who demonstrate understanding can do the following:

HS-LS2-1. Use mathematical and/or computational representations to support explanations of factors that affect carrying capacity of ecosystems at different scales. [Clarification Statement: Emphasis is on quantitative analysis and comparison of the relationships among interdependent factors including boundaries, resources, climate, and competition. Examples of mathematical comparisons could include graphs, charts, histograms, and population changes gathered from simulations or historical data sets.] *[Assessment Boundary: Assessment does not include deriving mathematical equations to make comparisons.]*

CHEMISTRY IN THE EARTH SYSTEM VIGNETTE 7.2: OCEAN ACIDIFICATION, A SYSTEMS-BASED APPROACH TO A GLOBAL PROBLEM

HS-ESS3-6. Use a computational representation to illustrate the relationships among Earth systems and how those relationships are being modified due to human activity. [Clarification Statement: Examples of Earth systems to be considered are the hydrosphere, atmosphere, cryosphere, geosphere, and/or biosphere. An example of the far-reaching impacts from a human activity is how an increase in atmospheric carbon dioxide results in an increase in photosynthetic biomass on land and an increase in ocean acidification, with resulting impacts on sea organism health and marine populations.] *[Assessment Boundary: Assessment does not include running computational representations but is limited to using the published results of scientific computational models.]*

HS-PS1-6. Refine the design of a chemical system by specifying a change in conditions that would produce increased amounts of products at equilibrium.* [Clarification Statement: Emphasis is on the application of Le Châtlier's Principle and on refining designs of chemical reaction systems, including descriptions of the connection between changes made at the macroscopic level and what happens at the molecular level. Examples of designs could include different ways to increase product formation including adding reactants or removing products.] *[Assessment Boundary: Assessment is limited to specifying the change in only one variable at a time. Assessment does not include calculating equilibrium constants and concentrations.]*

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-5] Using Mathematics and Computational Thinking [SEP-6] Constructing Explanations (for science) and Designing Solutions (for engineering) [SEP-7] Engaging in Argument from Evidence	LS2.A: Interdependent Relationships in Ecosystems ESS2.D: Weather and Climate ESS3.D: Global Climate Change PS1.B Chemical Reactions ETS1.B: Developing Possible Solutions ETS1.C: Optimizing the Design Solution	[CCC-3] Scale, Proportion and Quantity [CCC-4] Systems and System Models [CCC-7] Stability and Change

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Highlighted California Environmental Principles and 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 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; F-LB.1b, c; S-ID.6, 7; MP.4

CA CCSS for ELA/Literacy Connections: RST.9–10.2–10; SL.9–10.1b–d, SL.9–10.2–6; RST.11–12.2–10; SL.11–12.10.1b–d, 2–6

CA ELD Connections: ELD.PI.9–10.1, 2, 3

Introduction

Changes [CCC-7] in the world's oceans bring together all science and engineering disciplines and are an excellent way to introduce principles of chemical dynamics. While the concentration of CO_2 in our atmosphere is currently 40 percent higher than it was at the start of the Industrial Revolution, it would be even higher if it were not for the ocean. The ocean constantly exchanges CO_2 with the atmosphere so that the two are in equilibrium. This vignette explores how changes to the ocean's CO_2 concentration disrupt the entire biogeochemical system.

Length and position in course: This vignette describes 2–3 weeks of instruction and could serve as the main body of an instructional segment focusing on chemical equilibrium. This activity sequence is based closely on lessons from Systems Education Experiences in the Baliga Lab at Institute for Systems Biology. Please refer to their curricular pages for much greater detail: https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link34.

Prior knowledge: This activity has been shown to be more effective when students have existing understanding of systems and systems interactions. A simulation of social networks and cell phones provides an example with which students can easily relate (see Baliga Lab, Systems Education Experiences, Lesson 1: Cell phone network introduction at https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link35).

5E Lesson Design : This sequence is based on an iterative 5E model. See the "Instructional Strategies" chapter for tips on implementing 5E lessons.

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Days 1–2: Interconnected Systems

Students analyze news articles to obtain information that documents systems-level interactions between CO_2 emissions, ocean chemistry, organisms within the ocean, and human prosperity.

Days 3–4: Exploring CO_2

Students conduct a simple engaging activity to visualize the relationship between atmospheric CO_2 and ocean chemistry.

Day 5: Ocean Acidification Specifics

Students evaluate information from a movie, noting the way that scientific information is communicated. They identify chains of cause and effect relationships and relate them to Earth's system of systems.

Day 6: Planning and Conducting Investigations

Different groups of students investigate different interactions within the bio-geo-chemical system. They formulate their own research questions and design their own experiment.

Days 7–9: Online Simulations

Students explore complex feedbacks in a computer simulation. They manipulate environmental conditions to see the influence on ocean chemistry and ecosystems.

Day 10: Summit

Students play the role of different stakeholders. They report the findings of their experiments and use them as evidence to argue for a proposed solution that will reduce the impacts of ocean acidification.

Days 1–2: Interconnected systems

Anchoring phenomenon: Ocean life is dying off at alarming rates due to changes in the physical conditions of the ocean.

Ms. K is excited because today her class will begin to document the effects of the chemistry of CO_2 on a huge range of Earth's biological and chemical systems. Ms. K carefully selected a set of articles that illustrates a range of these interactions and assigns a different one to each student along with a sheet with a set of questions (https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link36). She allows students time to read the articles in class so that she can circulate and help some of the struggling readers. Ms. K has already discussed critical analysis of news stories in her class and asks students to share examples of how the author's qualifications and their intended audience affect the tone of the article. Each student must identify key words from the article and create a small network or concept map illustrating the connection between these key words. Students submit their key words to an online form and Ms. K monitors the results as they are submitted. She then pastes the key words into a word cloud generator (where the key words appear in an image with the font size of each word

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proportional to how often it is used). CO_2 is by far the largest word and a number of other words were utilized multiple times. While the word cloud is good for identifying the common threads, it fails at showing how these common ideas relate to one another. She divides the class up into groups of four and gives each group a large sheet of paper. Each group must arrange the submitted key words from the entire class into a single network or concept map. Students snap photos of their maps and upload them to the class Web page. For homework, they will refer to their map and write a short research proposal with an **argument [SEP-7]** justifying which key concepts they think are most important to investigate, and they brainstorm about how they could investigate such topics.

Days 3–4: Exploring CO_2

Investigative phenomenon: The concentration of CO_2 in water increases when the concentration of CO_2 in the air above it increases.

In this activity, students will explore sources and detection of CO_2 in the laboratory. Ms. K reminds students about the evidence that human activities emit CO_2 in the atmosphere. She asks them what their articles from the previous lesson said about how this relates to the ocean water. While the concentration of CO_2 in our atmosphere is currently 40 percent higher than it was at the start of the Industrial Revolution, it would be even higher if it were not for the ocean. The ocean constantly exchanges CO_2 with the atmosphere so that the two are in equilibrium. As the atmospheric CO_2 goes up, this temporarily disrupts the balance and causes more CO_2 to enter the oceans than leave. Ms. K assigns different students different sources of CO_2 (gas released by a baking soda/vinegar reaction, a combusting candle, dry ice sublimating, and yeast foaming). She tells them to **design an investigation [SEP-3]** that simulates an increase in CO_2 in the atmosphere and documents its effect on the pH of the ocean. In order to simulate changes to the atmosphere, Ms. K instructs students that all CO_2 should enter the water through contact with the air (their CO_2 source should not touch the water directly). She does not have access to pH probes, so she gives students droppers of Universal indicator and bromothymol blue along with flasks, tubing, and other supplies. Students find that the ocean becomes more acidic, which Ms. K explains is the reason that this environmental change is termed *ocean acidification.*

Investigative phenomenon: The concentration of CO_2 in Earth's ocean and atmosphere are both rising.

Ms. K then provides students actual data showing trends in CO_2 concentrations in the ocean and atmosphere as evidence of a balancing feedback between two of Earth's **systems [CCC-4]** that slows the rate of climate change (HS-ESS2-2). The ocean currently absorbs more than a quarter of the annual emissions of CO_2 from human activities. Students can add

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this fact to their quantitative **model [SEP-2]** of the carbon **cycle [CCC-5]** (HS-ESS2-6, ties to IS5 of the Life Science course). Once they enter the ocean, CO_2 molecules no longer have any impact on the atmospheric greenhouse effect. They do, however, cause significant **changes [CCC-7]** to the ocean water and life within it (EP&Cs II, III, & IV).

Day 5: Ocean Acidification Specifics

Investigative phenomenon: Fish and coral are dying as the concentration of CO_2 in the ocean rises. (Revisit the anchoring phenomenon in more detail.)

Students begin by **obtaining information [SEP-8]** about ocean acidification by watching a short video. Ms. K has students taking notes about different features of the film. One group records all the statistics in the film while another records facts that are stated but not supported by statistics. All groups track the cause and effect relationships described in the film. After the film, students pair up and discuss the parts of the movie that they found most powerful and the parts that they found weakest. They correlate those reactions with the observations of statistics and other statements not supported by numbers. It varies from group to group whether or not statistics or personal stories were more powerful. While science itself is most powerful when supported by robust quantitative data, **communicating [SEP-8]** science requires reaching out to peoples' hearts as well as their minds.

Working in teams, students complete a table summarizing all the **cause and effect [CCC-2]** relationships mentioned in the movie. They identify which spheres within Earth's systems are involved in each relationship, how CO_2 is involved, and how the change might affect humans. Students then annotate a diagram of the carbon cycle circling and labeling how the cause and effect relationships in the movie relate to sections of the carbon cycle. During class discussion, Ms. K asks students to chart chains of cause and effect relationships that involve different spheres in Earth's system of systems. She makes sure that students articulate can articulate the ways in which ocean acidification has large, global causes and that its effects reverberate throughout the system, including our economies.

Ms. K has students make a list of **questions [SEP-1]** about the cause and effect relationships they found most interesting. What would they like to find out more about? These questions will form the foundation of student research projects over the next few class sessions.

Days 6–9: Planning & Conducting Investigations

Investigative phenomenon: How will different interest groups be affected by ocean acidification and what can they do to minimize these effects?

Ocean acidification involves a huge range of organisms and people. Ms. K tells students that the class will divide up into different interest groups to investigate specific causes,

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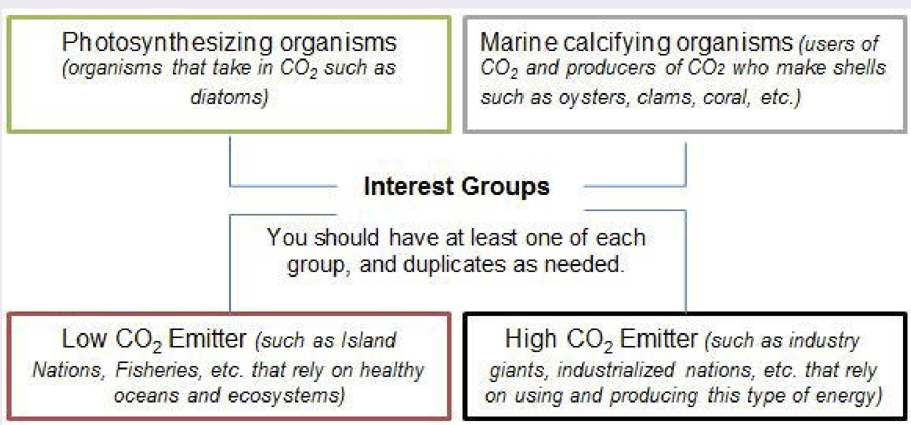
effects, and solutions of ocean acidification. At the end of the IS, the groups will come together for a final summit to present experimental results and provide recommendations for future actions. The main question all interest groups will address is, "What effect does the increasing atmospheric CO_2 have on the ocean and its subsystems?" Each group should focus in one specific effect and plan a detailed laboratory investigation. In other words, they will investigate the interaction between just two or three components of the biogeochemical system. Many of these interactions will be the cause and effect relationships that they recorded while watching the video. Ms. K has a presentation that helps students relate this experiment to systems thinking and gives guidance about refining research questions.

The class will have four main interest groups (figure 7.42). Even though all marine organisms are eventually affected by acidification through the food web, two categories of organisms at the base of many food chains are most fundamentally affected: photosynthesizing organisms that take in CO_2 and organisms whose survival depends on making carbonate shells (calcifying organisms). People are related to both the cause and the effects of ocean acidification. Two notable interest groups are those people responsible for most of the CO_2 emissions and those that depend most directly on ocean life for food (such as low CO_2 emitting island nations). Ms. K read through the questions submitted last class period and assigned students to one of four interest groups based on their questions.

Figure 7.42: Four Interest Groups



Source: Baliga Lab at Institute for Systems Biology 2013
Long description of Figure 7.42.

Investigative phenomenon: (Students investigate one interaction within the biogeochemical system using a laboratory experiment.)

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Ms. K asks students to list the type of things that they might be able to measure and manipulate in the laboratory in order to gain insight into their interest group's role in ocean acidification. Students will have access to a wide range of materials (see the materials list at https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link37) including living organisms like diatoms called Thaps and brine shrimp (with calcium carbonate shells), sources of carbon dioxide (identical to the investigation from Day 3), and tools and supplies to control the environmental conditions of the experimental atmosphere and ocean (including temperature, lighting, salinity, nutrient content of water, etc.). The photosynthesizing organisms group would likely investigate how changes in ocean pH affect their own growth or ways in which changes to their environment could promote their growth to help mitigate rising atmospheric CO_2. The marine calcifying organisms group would likely investigate the effects of a lower pH on their shells or growth. The High CO_2 emitters group could investigate ways in which they mitigate their emissions by promoting growth of photosynthesizing organisms or by exploring chemical reactions that capture their CO_2 emissions. They could also experiment by recording the CO_2 emissions of different alternative fuels such as ethanol, natural gas from Bunsen burners, or exploring the efficiency of various renewable energy sources. In previous years, some of Ms. K's High CO_2 groups pursued evidence supporting the claim that ocean acidification is not a problem. She encouraged these experiments and noticed powerful shifts in student thinking when their evidence contradicted this claim. The Low CO_2 emitters group might be concerned with the impact of acidification on their food supply and environment, so they will likely explore the impacts of CO_2 on one of the different classes of organisms at the base of the food chain. They also might want to explore just how low the pH of the ocean could get by testing how far the pH of the ocean can change since it is a buffered solution.

Ms. K walks around to each group, encouraging them to narrow down their investigation to two or three components of the system and asks them to formulate subquestions that their investigation will try to answer. For some groups, she offers a lot of guidance and gives them a menu of ideas they could consider. She helps them deal with logistics, and has a library (see Systems Education Experiences Lesson 5a https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link38) of background reading and laboratory protocols that she draws from to provide students extra resources. Students will need these to ensure that they can describe the specific chemical reactions occurring in their experiment.

As the groups perform their investigation over the next several days, Ms. K reminds students that their job is to (1) understand the details of their chemical system and be able to relate it to the broader problem of ocean acidification; (2) report their findings at the summit at the end of the session; and (3) Use their findings to inform a solution that can minimize the effects of ocean acidification. To accomplish this last task, they will need to think about how they can manipulate the conditions of the broader chemical system to change the amounts of acid in the ocean (HS-PS1-6). Some experiments are quicker, so those groups can proceed to completing online research from the next lesson.

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Day 10: Online research and computer simulations

Ms. K demonstrates a computer simulator that will allow students to explore the overall **effects [CCC-2]** of ocean acidification on different organisms and actions that people could take to slow acidification (HS-ESS3-6, HS-LS2-1, HS-ETS1-4, EP&Cs II, III) (see Institute for Systems Biology, Ocean Acidification: A Systems Approach to a Global Problem—Lesson 5b at https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link39 and Lesson 5c at: https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link40.) Students can add CO_2 until the atmospheric concentration matches possible emissions scenarios and examine the impact this will have on different populations of marine life (HS-ESS3-5). Students should try to relate the computer simulation to their physical experiment and use data from both to begin to explore possible solutions to ocean acidification.

Day 11: Summit

Students culminate the IS with a mock summit where they play the part of different stakeholders in the processes contributing to ocean acidification (EP&C V). Based upon their interest group, they can take up the role of residents of a small fishing village, oil company executives, marine geochemists, tour boat operators at the Great Barrier Reef. To engage in a meaningful **argument [SEP-7]**, they will need to **communicate information [SEP-8]** about their experiment and its relationship to their character's role (HS-ETS1-3). Though each stakeholder makes a contribution to the **system [CCC-4]**, students will need to break apart the problem into pieces and propose solutions that address the components that their character may be able to influence (HS-ETS1-2). They should support this proposed solution using evidence from their experiment and the online simulation.

Vignette Debrief

SEPs. Appendix 1 describes the progression of SEPs through the grade spans. At the end of this high school course, students should be able to demonstrate advanced forms of each SEP. The centerpiece of this vignette is an open-ended investigation that highlights two of SEPs related to experimental design. While students began asking simple questions in kindergarten, this vignette gives them the opportunity **to ask testable questions [SEP-1]** about the systems models of ocean acidification that they began to develop on Days 2 and 5. In elementary school, they received great guidance with planning simple investigations. They have progressed to the point that on Days 6–9, they **plan an investigation [SEP-3]** from scratch where the objective is to revise different interactions in a **model [SEP-2]** that will be used to **propose a solution [SEP-6]**. The activity culminates by highlighting two SEPs about communicating information and arguments on Day 10 in the Summit. They make and defend claims about the impacts of different human activities and create **arguments [SEP-7]** supporting a proposed solution to minimizing these impacts. They support these arguments by **communicating information [SEP-8]** about their experimental findings and evidence they **obtained [SEP-8]** from background research.

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DCIs. The vignette requires application of core ideas in all branches of science where human impacts on one part of Earth's system (ESS3.D) cause changes to ecosystems (LS4.D) in another part due to chemical reactions (PS1.B) within a complex bio-geo-chemical system (ESS2.A). Engineering and technology are key parts of analyzing the problem and designing solutions (ETS2.B). Computer simulations allow students to visualize the impacts of these systems and help them design and evaluate competing solutions to a major problem (ETS2.A).

CCCs. Ocean acidification is a **change [CCC-7]** to the equilibrium of a bio-geo-chemical **system [CCC-4]**. By the end of this high school course, students are ready to explore complex interactions within the system that create feedbacks, blurring the line between **cause and effect [CCC-2]**.

EP&Cs. Humans depend on ocean ecosystems for food and for its ability to buffer our effects on the carbon cycle (Principle I), while the oceans are clearly impacted by human behavior (Principle II). By assigning students to interest groups and asking them to play the role of different stakeholders, they begin to see the complex interdependencies inherent in a global problem like ocean acidification. In particular, the summit is an excellent example of Principle V that decisions are based on a wide range of considerations from ecological to economic.

CA CCSS Connections to English Language Arts and Mathematics. In the vignette, students are tasked with reading articles about the effects of the chemistry of CO_2 on a huge range of Earth's biological and chemical systems and analyzing the author's qualifications and intended audience (RST.9–10.2, 10, RST.11–12.2, 10). Students also watch a film about ocean acidification and record the stated facts that include statistics and those that do not. They analyze the validity of those statistics and create a cause and effect table from information in the video (SL.9–10.2). The instructor divides the students into groups to plan a detailed laboratory investigation that focuses on one specific effect that increasing atmospheric CO_2 has on the ocean and its subsystems. The instructor also demonstrates a computer simulation that models the overall effects of ocean acidification (MP.4, N-Q.1, S-ID.6, 7, F-LE.1b,c). Students participate in a mock summit in which students express the point of view of stakeholders involved in the processes of ocean acidification (SL.9–10.1, SL.11–12.1).

Resources:

This activity sequence is based closely on lessons from Systems Education Experiences at the Baliga Lab at Institute for Systems Biology 2017. Please refer to them for much greater detail https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link41. They provide a recorded webinar walking through the lesson sequence and a number of downloadable resources. *Ocean Acidification: A Systems Approach to a Global Problem* was made possible by National Science Foundation through awards OCE 0928561, MCB 1316206, & PLR 1142049.

Physics of the Universe: Integrating Physics and Earth and 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 historical background and details 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 the California Next Generation Science Standards (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 demonstration can capture such a rich process, it is hard to claim that this demonstration is truly exciting or evokes 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 who 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 learning 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. 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 in which to address topics because phenomena need to be relevant to the students who 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 (PE). 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 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.

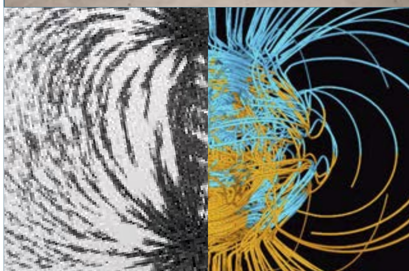
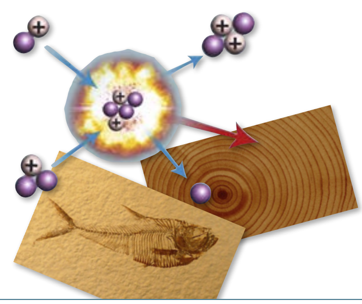
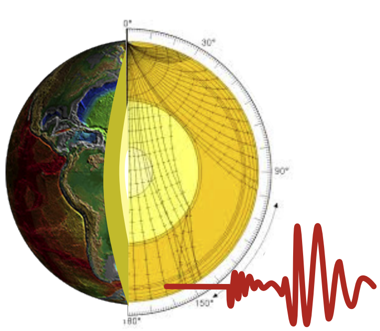
This example course is divided into instructional segments (IS) centered on questions about observations of a specific phenomenon. Different phenomena require different amounts of classroom investigative time to explore and understand, so each instructional segment should take a different fraction of the school year. As students achieve the performance expectations within the instructional segment, they uncover DCIs from physical science, Earth and space science, and engineering. Students engage in multiple practices in each instructional segment, not only those explicitly indicated in the performance expectations. 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 performance expectation, 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 course 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 and Earth and space science DCIs emphasize how discoveries in those disciplines 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 EP&Cs). A major emphasis in the first several instructional segments of this course is one topic, relevant to society as a whole, in which 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 **systems [CCC-4]**. The theme is not all-encompassing, as many of the performance expectations pertain to core ideas that are disjointed from renewable **energy [CCC-5]**.

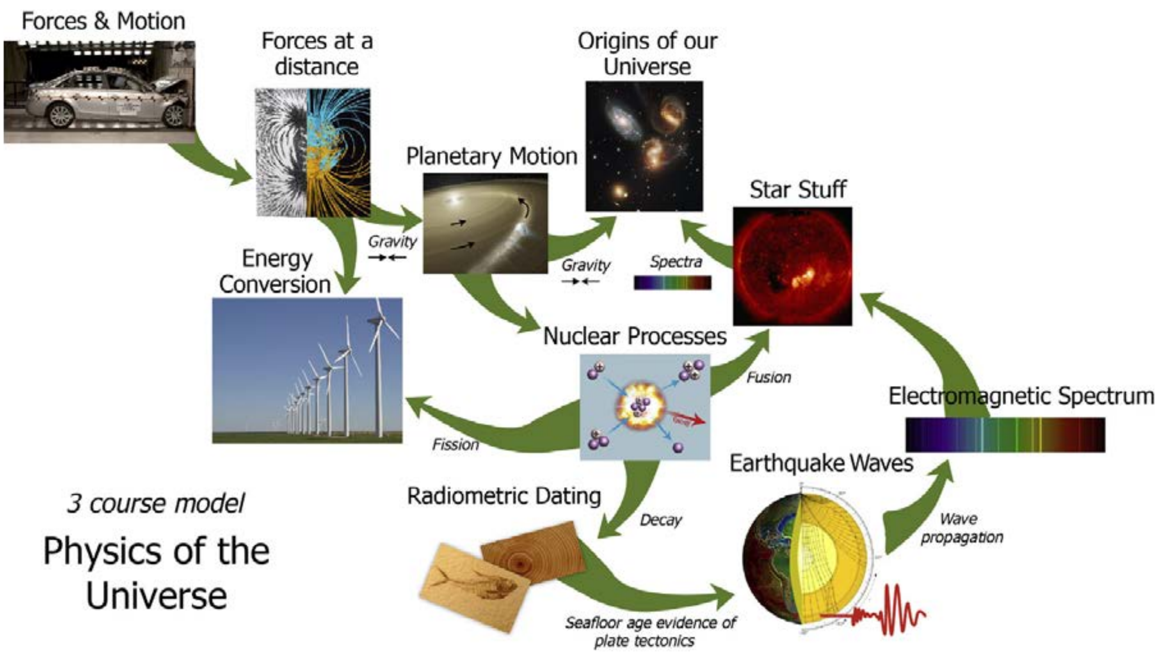
Table 7.6. Overview of Instructional Segments for High School Three-Course Model Physics of the Universe

	**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 its conversion through different stages of power generation. 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 Administration 2016; adapted from Black and Davis 1913, 242, fig. 200; adapted from NASA 2003a; Leaflet 2004; adapted from Wikimedia Commons 2011; adapted from Sorenson 2012; adapted from Jordan 2010; adapted from National Oceanic and Atmospheric Administration and National Centers for Environmental Information with Cooperative Institute for Research in Environmental Science 2008; adapted from Ezekowitz 2008; NASA, ESA, and the Hubble SM4 ERO Team/Space Telescope Science Institute 2009

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



Sources: National Highway Traffic Safety Administration 2016; adapted from Black and Davis 1913, 242, fig. 200; adapted from NASA 2003a; Leaflet 2004; adapted from NASA/JPL-Caltech 2006; NASA, ESA, and the Hubble SM4 ERO Team/Space Telescope Science Institute 2009; Wikimedia Commons 2011; adapted from Sorenson 2012; adapted from Jordan 2010; National Astronomical Observatory of Japan, Institute of Space and Astronautical Science/Japan Aerospace Exploration Agency 2006; adapted from National Oceanic and Atmospheric Administration and National Centers for Environmental Information with Cooperative Institute for Research in Environmental Science 2008; adapted from Ezekowitz 2008; NASA 2015
Long description of Figure 7.43.

IS1

Physics of the Universe Instructional Segment 1: Forces and Motion

What does a mountain peak have in common with a car (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]**, both are 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 do the following:

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.

PHYSICS OF THE UNIVERSE INSTRUCTIONAL SEGMENT 1: FORCES AND MOTION

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-4] Analyzing and Interpreting Data [SEP-5] Using Mathematics and Computational Thinking [SEP-6] Constructing Explanations (for science) and Designing Solutions (for engineering)	PS2.A: Forces and Motion PS2.B: Types of Interactions ETS1.A: Defining and Delimiting Engineering Problems ETS1.B: Developing Possible Solutions ETS1.C: Optimizing the Design Solution	[CCC-2] Cause and Effect [CCC-4] Systems and System Models

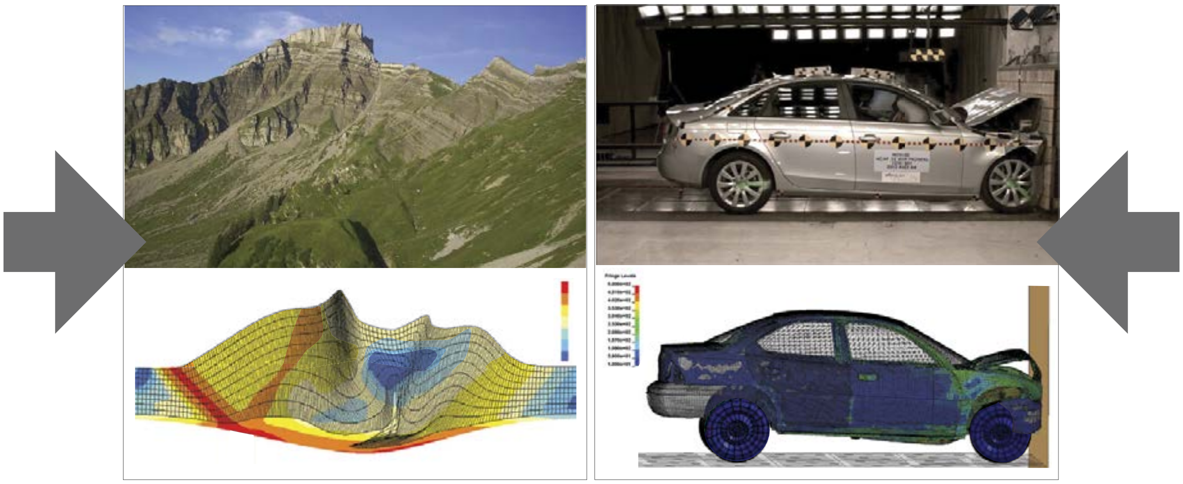
Highlighted California Environmental Principles and Concepts:
Principle V Decisions affecting resources and natural systems are based on a wide range of considerations and decision-making processes.

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

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

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 Administration 2016; Willett 1999; Livermore Software Technology Corporation 2017
Long description of Figure 7.44.

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 [SEP-5]** 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.

Table 7.7. Newton's Laws of Motion

First 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
Second Law **Definition of Force**	$F = ma$. An object's acceleration, a, depends on its mass, m, and the applied force, F.
Third 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 uses 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 for 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 https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link42) 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 versus time, speed versus time and acceleration versus 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 with opportunities not only to perform calculations, but to test them 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 on 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 to actually build 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 following 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 ran an efficient technology-enhanced classroom where he was 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. wanted 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 entered the room, they opened the class Web site on their mobile devices and found the day's agenda. Each group of three students was 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 Valley, Yosemite Valley, Rhone Valley), or plateaus (Kukenan Tepui, Monte Roraima, Table Mountain, Auyantepui). As the opening bell rang, students were already actively searching their geomorphic features. Mr. H. used a remote desktop to freeze their devices so he could clarify the instructions printed on the agenda Web page. Each team was to develop a tour-guide script that one of their members would read as they introduced their geomorphic feature to the class. Each group was to create a narrated animated tour in which they provided voiceovers, and descriptive pop-up balloons as they "flew" their audience around the globe in a video-like experience. Each animated fly-by or float-by tour had to include a description of the constructive forces (such as volcanism and

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

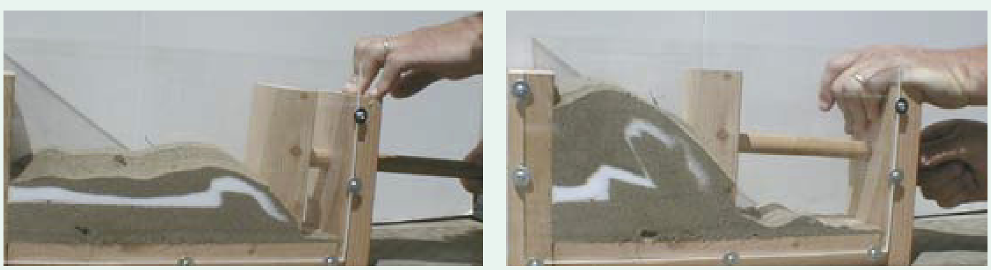
tectonic movements) and destructive mechanisms (such as weathering, landslides, and coastal erosion) that have shaped their feature (HS-ESS2-1). Students worked throughout the period, integrating their knowledge of plate motions and surface processes with the features they observed. Students were required 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 for ELA/Literacy SL.11–12.4–5.

The following day, students proudly presented their fly-by videos, providing the class with an introduction to key oceanic and continental geomorphic features. Following the video presentations, Mr. H. asked students to describe how Newton's laws helped explain the formation of such features. Students typed their responses into an online form that allowed Mr. H to monitor their thinking in real-time. It soon became clear that although his students seem to have a good grasp of Newton's laws as measured by a traditional assessment, and although they seemed to have a good understanding of key geomorphic features, they appeared 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. proceeded 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, homogeneous, 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. presented a squeeze box with a screw mechanism (figure 7.45).

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

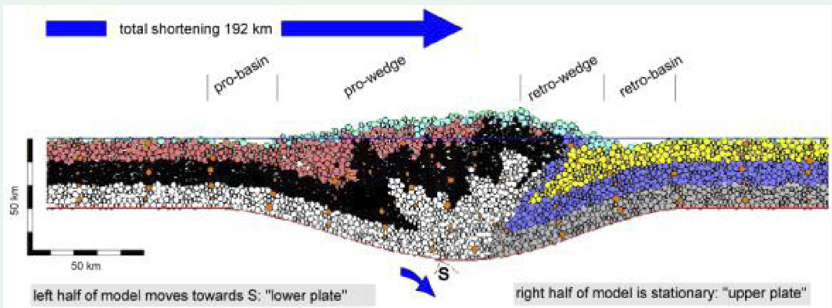


Source: Muller 2000. Used with permission, from the Squeeze Box Science Snack, https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link43 by Eric Muller, © Exploratorium, https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link44
Long description of Figure 7.45.

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

Layers of dark and light sand were placed in alternating horizontal layers in the box and pressure applied with a screw mechanism. As the crank turned, layers deformed, simulating geological folding and mountain building. Unlike other physics problems the students had encountered using rigid objects, the sand was 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 showed an example in which scientists used this sort of **computational thinking [SEP-5]** by means of computer simulations called *discrete element analysis*. (figure 7.46)

Figure 7.46: Computer Model of Layers Deforming During Continental Collision



Source: Handy 2006
Long description of Figure 7.46.

Mr. H asked students to work in pairs to label the forces acting on a small section of sand near the middle of the model. Students uploaded photos of their diagrams to the class Web page so that everyone could see their peers' work. Mr. H selected two student diagrams to show side-by-side and asked 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 forgot to include the force of the opposing wall. Mr. H asked students to consider the vector sum of the forces to make sure it pointed in the same direction as the change in motion.

Figure 7.47: Example Student Diagrams

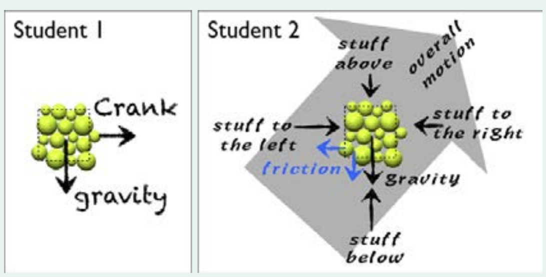


Diagram by M. d'Alessio
Long description of Figure 7.47.

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

Mr. H next asked students how Newton's second law (*F*=*ma*) applied to this situation using the online student response form. This time, many students mentioned that force (applied through the screw) caused the mass of the individual particles (sand) to accelerate as evidenced by the movement of layers within the box. Mr. H told the students that there was some truth to that statement, but he disagreed that this explanation described most of the motion within the system. He challenged his students to **identify the evidence on which he based his argument [SEP-7]**. They were confused at first, but Mr. H walked around as teams of students discussed his statement. He asked them leading questions, such as "How would you describe the velocity of the wall?" Each team eventually realized 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 moved constantly but did not deform, so it too did not accelerate. At any given time, only a small fraction of the model was accelerating. The same thing happened in the real world. Mr. H showed observations from precise GPS measurements that revealed that most plates move at constant rates in constant directions for decades (i.e., no acceleration). Clearly forces are being applied to the **system [CCC-4]**, so why doesn't it accelerate despite the constant force applied on the edges? Some students recognized friction as being important as the grains of sand slid past one another. They reasoned 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 performance expectation 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; 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 divide the entire 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 chapter 11 of this 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 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

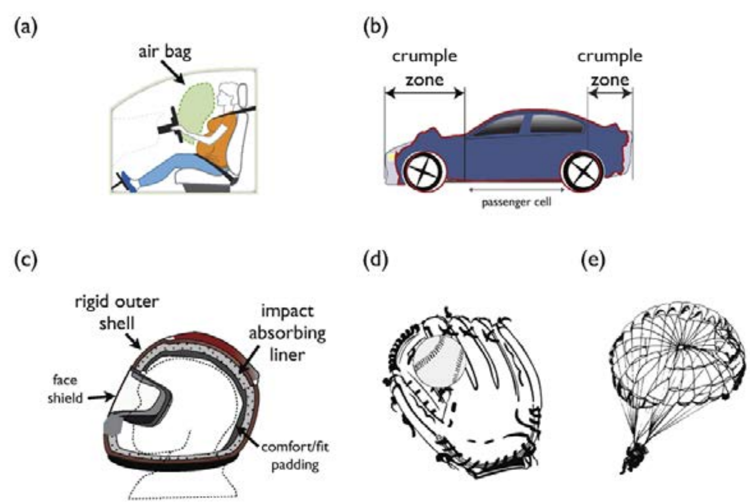
Students learn physics principles such as impulse and momentum while simultaneously learning engineering design and testing principles while designing and developing devices for challenges such as the classic egg-drop contest. *Source*: Buggy and Buddy 2014

Long description of Figure 7.48.

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 can label the 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 ($F\Delta t$) and is equal to the change in momentum of the object to which the force is applied ($m\Delta v$). 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*: M. d'Alessio with images from National Highway Traffic Safety Administration 2015; adapted from KTEditor 2014; adapted from OpenClipart-Vectors 2013b; Clker-Free-Vector-Images 2012; OpenClipart-Vectors 2013a; Headquarters Department of the Army 2012

Long description of Figure 7.48.

IS2

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

Instructional segment 1 introduced 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. Instructional segment 2 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 do the following:

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.

PHYSICS IN THE UNIVERSE INSTRUCTIONAL SEGMENT 2: FORCES AT A DISTANCE

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-5] Using Mathematics and Computational Thinking [SEP-8] Obtaining, Evaluating, and Communicating Information	PS2.B: Types of Interactions ESS1.B: Earth and the Solar System	[CCC-1] Patterns [CCC-2] Cause and Effect: Mechanism and Explanation [CCC-3] Scale, Proportion, and Quantity [CCC-6] Structure and Function

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

CA CCSS for ELA/Literacy Connections: RST.11–12.1, WHST.9–12.2.a–e

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

At the middle grades level, students established 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 instructional segment extends those skills by providing mathematical **models [SEP-2]** of these forces. Though students' everyday experiences 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.

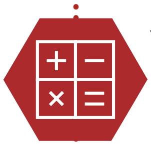
Science and Engineering Practices and the History of Gravity

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 the 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 twenty-first 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). In the middle grades, 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 Connections

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 they only had empirical evidence and 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.

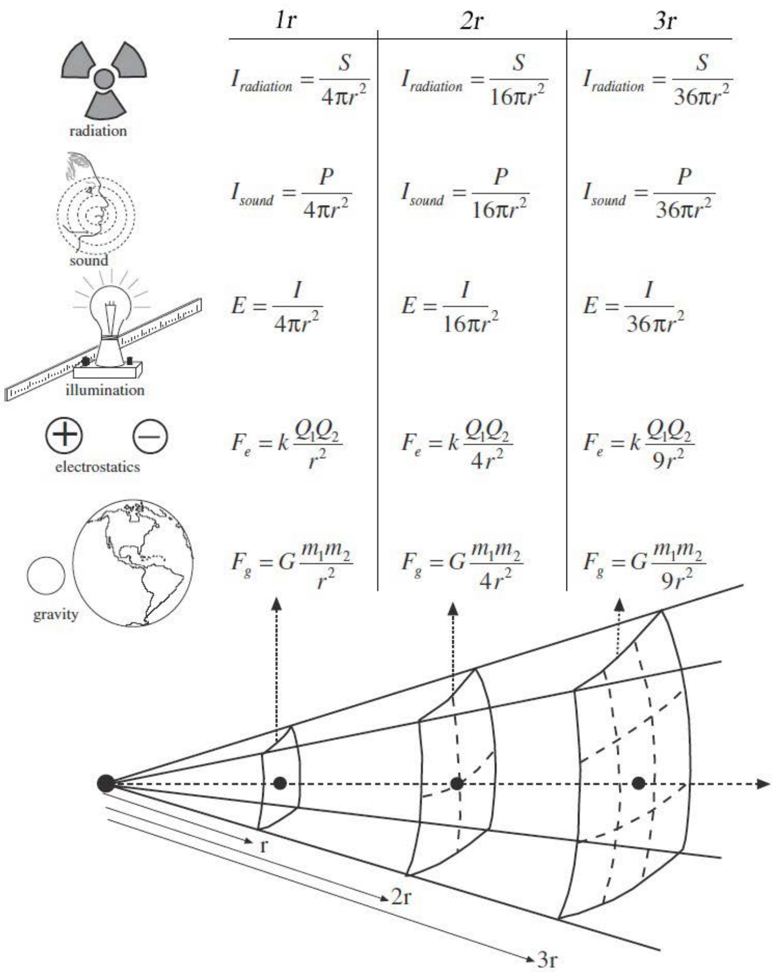
Asking students to identify the scientific principles that engineers apply to design and improve such technologies provides opportunities to review prior learning and recognize the value of science in everyday life. It also opens the door to understanding the **interdependence of science, engineering, 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 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 firsthand 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 https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link45) and interactive simulations (see the Concord Consortium Electrostatics at https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link46).

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
Long description of Figure 7.50.

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 asked her students to imagine throwing a rock into a glassy-smooth pond. Waves would 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 further 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 provided students access to all the equipment in the lab and asked them to develop a **model [SEP-2]** that illustrated how intensity varies with distance. Tom and Min used a marker to color a square on a balloon and proceeded to inflate the balloon to observe how the color of the square got lighter as the balloon was inflated. As Joshua and Maria observed Tom and Min, they got the idea to do the same, but used their cell phones to video their balloon as it is inflated so that they would have a permanent record to share with the class. Julia and Tae realized that Joshua and Maria had a good idea, but were lacking a scale, and improved upon their design by including a ruler in the background. Ms. C subsequently asked all three teams to share their ideas, and then asked Julia and Tae to wirelessly send their movie to the data projector so the class could observe the model (CA CCSS for ELA/Literacy SL.11–12.5). Students then estimated the surface area of the balloon at three different radii (CA CCSSM G-GMD.1) and noted how the intensity of the marker color decreased significantly with increasing radius (CA CCSSM G-GMD.5).

Applications of Gravitational Force: Planetary Motions

To verify that his mathematical model of gravitation was correct, Newton compared his results to observations of planetary orbits. If gravity were holding the planets in their orbits, Newton should be able to show it. He rearranged his equation to compare its prediction to the previous work of Johannes Kepler, who had 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 to interpret 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 7.8 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 to 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, also in table 7.8). But students can use measurements of the Moon to predict the height of satellites in geosynchronous orbit, which have an orbital period of exactly one day, allowing them to always be in the same position in the sky. Satellite television receives signals from these satellites. Alternatively, students can use 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 (dwarf planet)	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 the 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 satellites will stay in orbit and the investment is not lost. 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?

(Note: Appendix 3 in this 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 [CCC-4]**:

> 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 [S]un, 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 a strong influence on Earth's ice age **cycles [CCC-5]**.

Applications of Electromagnetic Forces

Up to this point, this instructional segment 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 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 discipline 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 performance expectation 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 forces 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. Performance expectation 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) at the macro-level and that these properties make certain materials good candidates for specific technical applications.

IS3 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 uses 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 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 do the following:

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-PS3-3. 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-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-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.]*

PHYSICS IN THE UNIVERSE INSTRUCTIONAL SEGMENT 3: ENERGY CONVERSION AND RENEWABLE ENERGY

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-3] Planning and Carrying Out Investigations [SEP-5] Using Mathematics and Computational Thinking [SEP-6] Constructing Explanations (for science) and Designing Solutions (for engineering)	PS2.B: Types of Interactions PS3.A: Definitions of Energy PS3.B: Conservation of Energy and Energy Transfer PS3.C: Relationship Between Energy and Forces PS3.D: Energy in Chemical Processes and Everyday Life ETS1.A: Defining and Delimiting Engineering Problems ETS1.B: Developing Possible Solutions ETS1.C: Optimizing the Design Solution	[CCC-2] Cause and Effect: Mechanism and Explanation [CCC-4] Systems and System Models [CCC-5] Energy and Matter: Flows, Cycles, and Conservation

Highlighted California Environmental Principles and 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.

PHYSICS IN THE UNIVERSE INSTRUCTIONAL SEGMENT 3: ENERGY CONVERSION AND RENEWABLE ENERGY

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

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

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 can be neither created nor destroyed. **Conservation of energy [CCC-5]** requires that changes in energy within a **system [CCC-4]** must be balanced by **energy flows [CCC-5]** into or out of the system by radiation, mass movement, external forces, or heat flow. The vignette for the physics course in the high school four-course model (chapter 8) provides a framework for discussing many of these energy forms and how they convert from one to another. This instructional segment 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 in use. 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 (EP&C V) because each of these **energy [CCC-5]** sources has advantages and disadvantages (ESS3.A). In 2013 more than half of the electricity in California was generated from fossil fuels (California Energy Commission Energy Almanac 2016). Many fossil fuel power plants emit toxic pollutants and can impact the health of ecosystems and people nearby (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 https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link47) 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; EP&C III; High School Three-Course Model Chemistry in the Earth System 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 are available for teaching about different electricity generation strategies, including formats in which students debate the relative costs and benefits of each energy source (HS-ESS3-2) (see National Energy Education Development Project, Great Energy Debate https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link48).

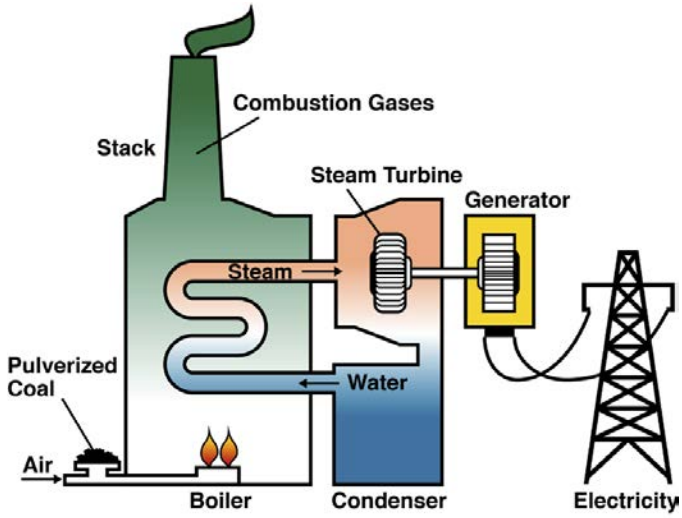
The Physics of Power Plants

A power plant can be thought of as 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).

In the middle grades, 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 performance expectations explicitly state that calculations are excluded from the middle grades 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 grades performance expectations 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 performance expectation 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 produce electricity (most fossil fuel, nuclear, geothermal, and concentrated solar power plants fit in this category). They usually heat water to form 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 convert 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 turns the rotor of a generator to convert the kinetic energy into electricity. This process will not be 100 percent efficient because molecular collisions result in energy being transferred to particles moving in random directions again, reducing the total energy available to move the rotor. 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



Long description of Figure 7.51.

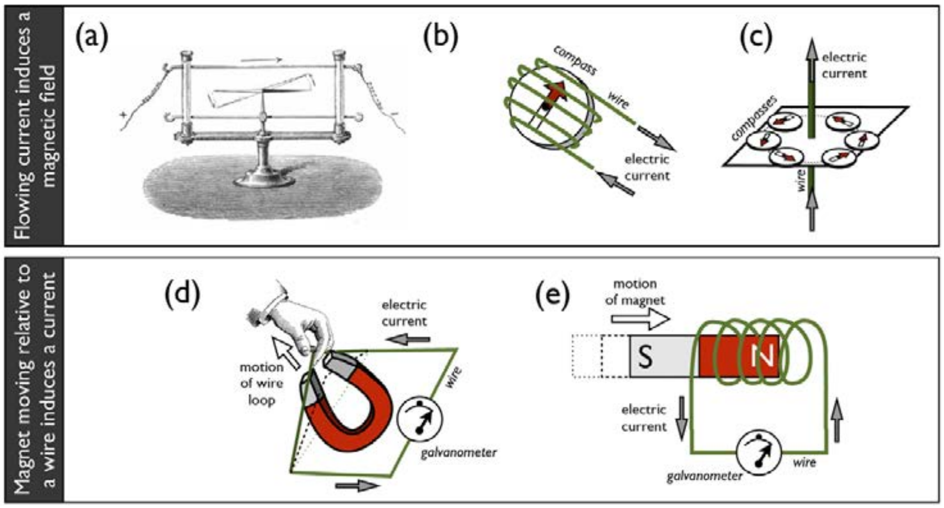
Converting Kinetic Energy to Electricity

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. To overcome this preconception, students must replace that notion with a correct model for conversion of kinetic energy of objects into 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 that 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). Students 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): Ørsted's experiment illustrates that an electric current generates a magnetic field. (b and 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*: M. d'Alessio with images from Privat-Deschanel 1876, 656, fig. 456 and OpenClipart-Vectors 2013c.
Long description of Figure 7.52.

Students can also place iron filings on a glass plate that rests 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 in 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 instructional segment 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 key ingredients of 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 in which 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 atom to be in a configuration with holes that can accept an additional electron. Adding other specific elements causes the silicon atoms in the lattice to have 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. Then, when light hits the atoms in this material, the free electrons are repelled by the extra electrons in one layer and automatically move toward 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 in 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 school is located wanted to switch to 100 percent clean and renewable energy. They were 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 divided the class into small groups and she assigned each one to either create a proposal for wind energy or a plan for hydroelectric power. Teams began by using **mathematical thinking [SEP-5]** to calculate the amount of energy their proposed project would generate. The hydroelectric group assumed that the dams would harness gravitational potential energy and used the appropriate equations to evaluate the energy produced by different height dams (Energy = mass x g x height, where the water mass was determined by the average annual flow rate on the river calculated using data collected by a United States Geological Survey (USGS) stream gauge that was available on the Internet). The wind energy group assumed that the kinetic energy of the air would be harnessed and used 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 speed was calculated using the average values from a nearby weather station that had posted hourly data on the Internet).

Investigative phenomenon: Electric generators are not 100 percent efficient.

Mrs. G taught the students about the concept of efficiency when it came to electric power generation in which only a fixed **proportion [CCC-3]** of the energy would be successfully converted to electricity (while a large fraction would be wasted as heat).

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

Each team **obtained information [SEP-8]** about the efficiency of their energy generation technology and used it update their estimate of the electrical energy they could generate. With these basic calculations, each team had to develop a specific proposal for a power plant that would provide 100 percent of the city's energy. The wind teams had to decide how many windmills, and the diameter of the blades. The

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

hydroelectric teams had to decide how many dams and their heights. Each team produced a report outlining the benefits of their plan. The class then hosted a town hall meeting during which teams **communicated [SEP-8]** their plans and presented an argument that their proposal was better than the competing plans. This **argument had to be supported by evidence [SEP-7]** that went beyond the simple energy calculations but also took into account the relative benefits and impacts of each technology on natural systems (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 (EP&C V). Students could have used a spreadsheet program to try to quantify some of these effects as they compared 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 the High School Four-Course Model—Physics course (chapter 8) in this 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 the beginning of this instructional segment, 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 instructional segment 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 instructional segment. 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 use existing computer simulations to investigate the impact of these different energy solutions (HS-ETS1-4).

IS4

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 instructional segment, 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 do the following:

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)

PHYSICS IN THE UNIVERSE INSTRUCTIONAL SEGMENT 4: NUCLEAR PROCESSES AND EARTH HISTORY

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.]*

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-2] Developing and Using Models [SEP-6] Constructing Explanations (for science) and Designing Solutions (for engineering) [SEP-7] Engaging in Argument from Evidence	ESS1.C: The History of Planet Earth ESS2.A: Earth Materials and Systems ESS2.B: Plate Tectonics and Large-Scale System Interactions PS1.A Structure and Properties of Matter PS1.C: Nuclear Processes	[CCC-1] Patterns [CCC-5] Energy and Matter: Flows, Cycles, and Conservation [CCC-7] Stability and Change

Highlighted California Environmental Principles and 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 CCSS for ELA/Literacy Connections: SL.11–12.4; RST.11–12.1, 8; WHST.9–12.2.a–e, 7, 9

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

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

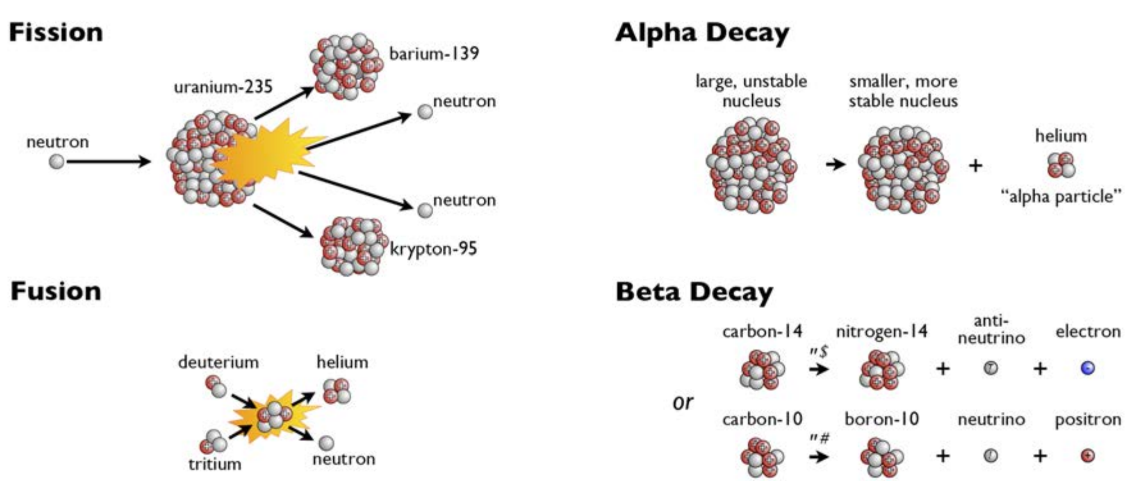
Changes in the nucleus occur at a length **scale [CCC-3]** too small to observe directly, but students can detect **evidence [SEP-7]** of these processes by looking at energy and matter that radiate out of the nucleus as a result of these changes. One can think of these emissions as an **effect [CCC-2]** and **develop a model [SEP-2]** that **explains [SEP-6]** the **cause [CCC-2]**. Students begin the instructional segment by making observations of a cloud chamber (see MIT Video, *Cloud Chamber* at https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link49, 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, Smartphone radiation detector app tests positive at https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link50). With these observations, students now **obtain information [SEP-8]** about the discovery of radioactivity and how scientists in the late 1800s 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 have identified only four fundamental interactions, 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 instructional segment 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 **distance 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 nuclei changing in various 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; adapted from Pbech 2008; adapted from Thomas Jefferson National Accelerator Facility—Office of Science Education 2015a, 2015b
Long description of Figure 7.53.

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 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 succeed in making it 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 is required for nuclei to reach speeds fast enough to achieve fusion. Unless the fusion device is extremely efficient, it ends up taking more energy to start the fusion process 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 in which 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 causes 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 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 to be more 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 very slowly, primarily by alpha, beta, and gamma decay. Reactors produce most of their energy by inducing fission, accomplished typically by separating uranium-235 (a nucleus with 92 protons and 143 neutrons) from other isotopes of uranium with different numbers of neutrons. The naturally occurring mix of uranium isotopes absorbs neutrons, preventing the fission process from occurring too quickly. However, when fission occurs in one atom of purified uranium-235, neutrons that are emitted are likely to collide with other uranium-235 atoms and induce fission. As a result, energy release can be maintained at a rate far above the typical background level for naturally occurring mixtures of uranium isotopes. 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://www.cde.ca.gov/ci/sc/cf/ch7.asp#link51).

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 performance expectations related to radiometric dating require that students 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 decays 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 six protons and eight 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://www.cde.ca.gov/ci/sc/cf/ch7.asp#link52) 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: https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link53), 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. Extra or missing daughter products that are not properly accounted for 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 https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link54). 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 performance expectation was written by the authors of the 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 https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link55).

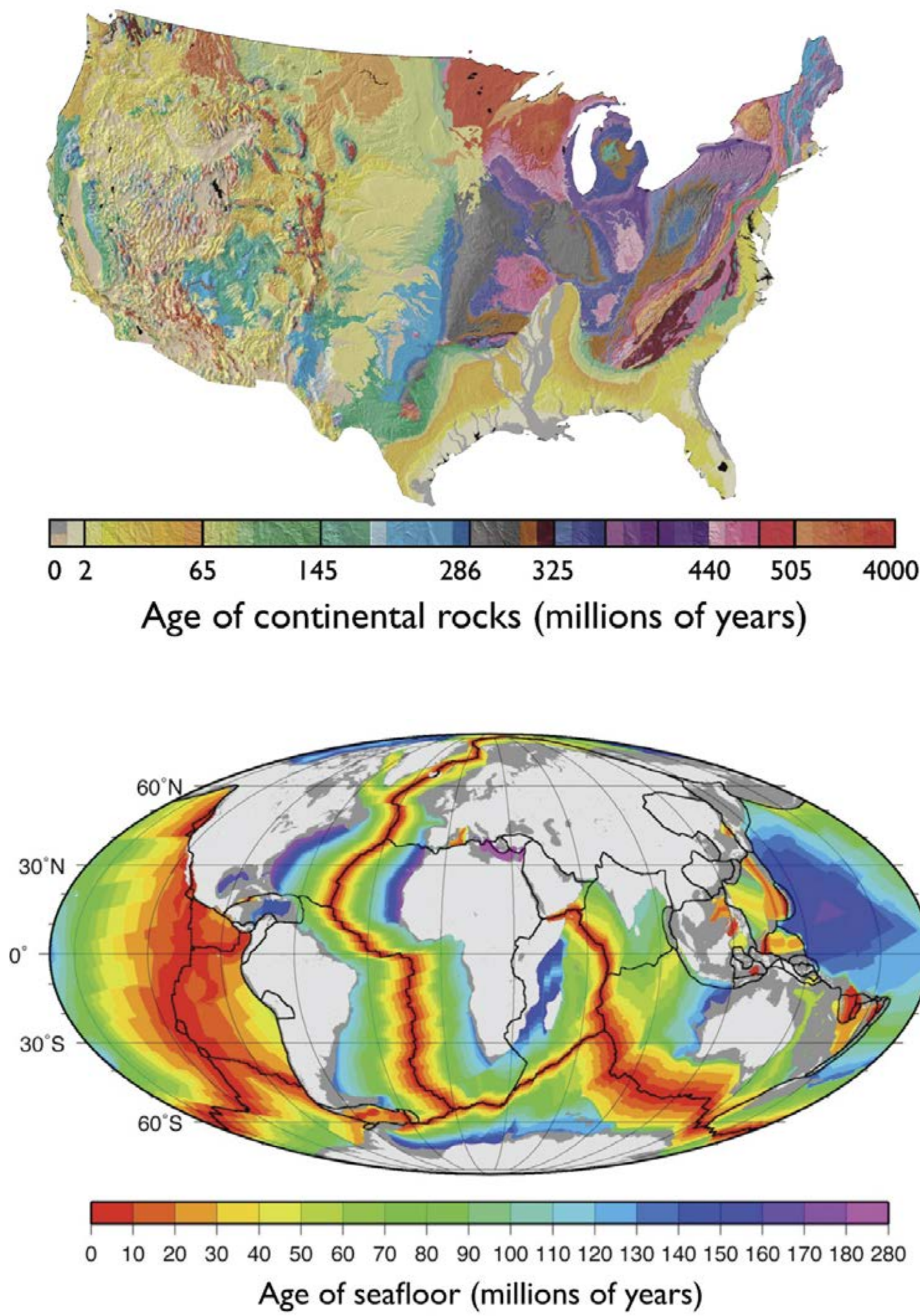
Since Earth formed, its surface has been constantly reshaped. We know this, in part, by evidence from radiometric dating. Plate tectonics is one process that actively moves and deforms rocks, and students **analyzed [SEP-4]** a range of data types supporting this theory in the middle grades (MS-ESS2-3). In high school, 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 United States 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 https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link56) 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 United States 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?

The seafloor, however, is much younger (no rock being older than 280 million years) and shows 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 are much older than those found on today's continents. So what happened to the rest of the old seafloor? A clue comes from the fact that ages of rocks on the seafloor typically progress in a logical order in a symmetrical **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 has been no accumulation of 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 constantly move away from the middle of the ocean. At the same time, older crust must therefore be sinking. This is expected because the crust becomes denser as it cools over time. Ultimately, the seafloor is subducted at an active plate boundary, which explains why there are no older seafloor ages). Students can measure the length of crust from the mid-ocean ridge and they know its age at different points; with this information 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 United States (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 2008
Long description of Figure 7.54.

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

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

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

Guiding Questions

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

Performance Expectations

Students who demonstrate understanding can do the following:

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

HS-PS4-1. Use mathematical representations to support a claim regarding relationships among the frequency, wavelength, and speed of waves traveling in various media. [Clarification Statement: Examples of data could include electromagnetic radiation traveling in a vacuum and glass, sound waves traveling through air and water, and seismic waves traveling through the Earth.] *[Assessment Boundary: Assessment is limited to algebraic relationships and describing those relationships qualitatively.]*

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

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

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

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

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

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

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

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

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

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

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

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

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

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

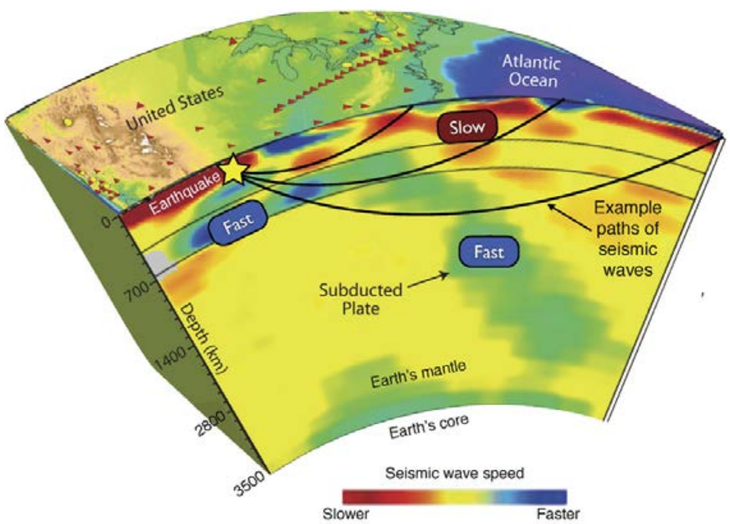
At the high school level, students can describe a wave as a disturbance or oscillation that transmits energy without transmitting matter. Mechanical waves travel through a medium, temporarily deforming the material. Restoring forces caused by elastic properties in the medium then reverse this deformation.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

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

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

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

Figure 7.55. Seismic Tomography Reveals Evidence of Plate Tectonics



Seismic waves move more quickly or more slowly as they move through different materials. Seismologists use this fact to map out the structure of Earth's interior. This image reveals evidence of plate tectonics and California's geologic history. The remnants of a large plate sinking beneath North America is believed to be the Farallon Plate that used to subduct off the coast of California (a process that created the massive granitic rocks of the Sierra Nevada). *Source*: van der Lee and Grand n.d. Long description of Figure 7.55.

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

PHYSICS IN THE UNIVERSE VIGNETTE 7.3: SEISMIC WAVES

Performance Expectations

Students who demonstrate understanding can do the following:

HS-PS4-1. Use mathematical representations to support a claim regarding relationships among the frequency, wavelength, and speed of waves traveling in various media. [Clarification Statement: Examples of data could include electromagnetic radiation traveling in a vacuum and glass, sound waves traveling through air and water, and seismic waves traveling through the Earth.] *[Assessment Boundary: Assessment is limited to algebraic relationships and describing those relationships qualitatively.]*

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

PHYSICS IN THE UNIVERSE VIGNETTE 7.3: SEISMIC WAVES

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

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

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

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

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

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

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

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

PHYSICS IN THE UNIVERSE VIGNETTE 7.3: SEISMIC WAVES

Introduction

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

Day 1: Observing Earthquakes

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

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

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

Day 4: Digital Versus Analog Seismic Information

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

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

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

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

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

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

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

Day 1: Observing Earthquakes

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

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

PHYSICS IN THE UNIVERSE VIGNETTE 7.3: SEISMIC WAVES

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

Figure 7.56: Video Clip of a Person Experiencing an Earthquake

Source: d'Alessio and Horey 2013
Long description of Figure 7.56.

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

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

Figure 7.57: Measurements of an Earthquake from Different Locations

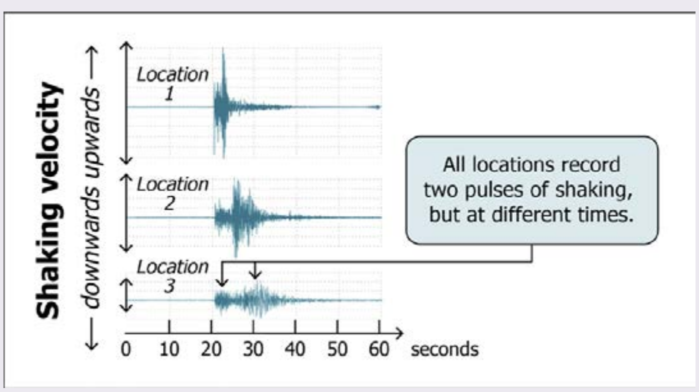


Diagram by M. d'Alessio
Long description of Figure 7.57.

PHYSICS IN THE UNIVERSE VIGNETTE 7.3: SEISMIC WAVES

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

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

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

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

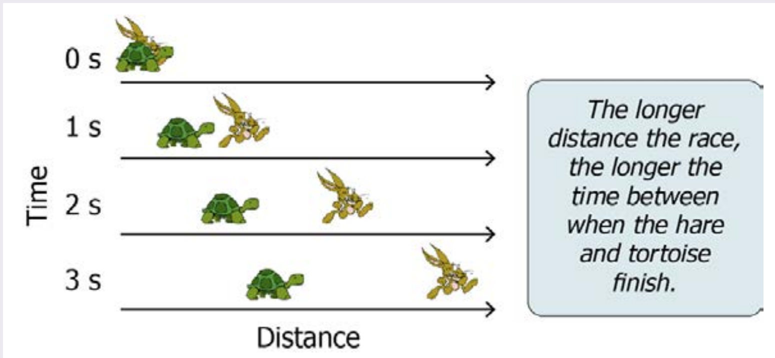

Diagram by M. d'Alessio
Long description of Figure 7.58.

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

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

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

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

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

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

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

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

Day 4: Digital Versus Analog Seismic Information

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

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

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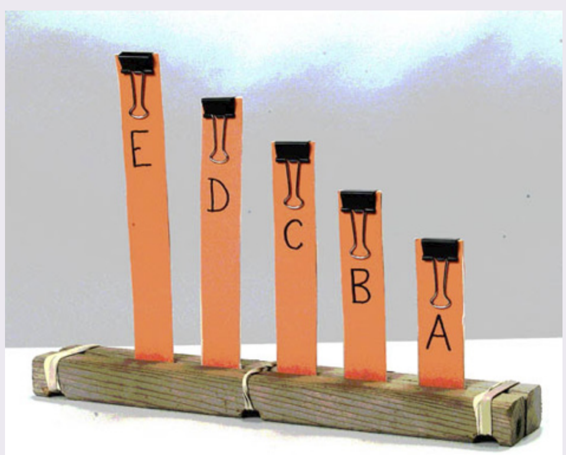
earthquakes with magnitude 5 and 8 could both cause damage yet have amplitudes that differ by a factor of 1000, digital encoding is the best strategy for transmitting seismic waves. And since the information is already encoded digitally, it is easy for a computer to process it and issue an earthquake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

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

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

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

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



Source: IRIS 2014
Long description of Figure 7.59.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

PHYSICS IN THE UNIVERSE VIGNETTE 7.3: SEISMIC WAVES

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

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

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

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

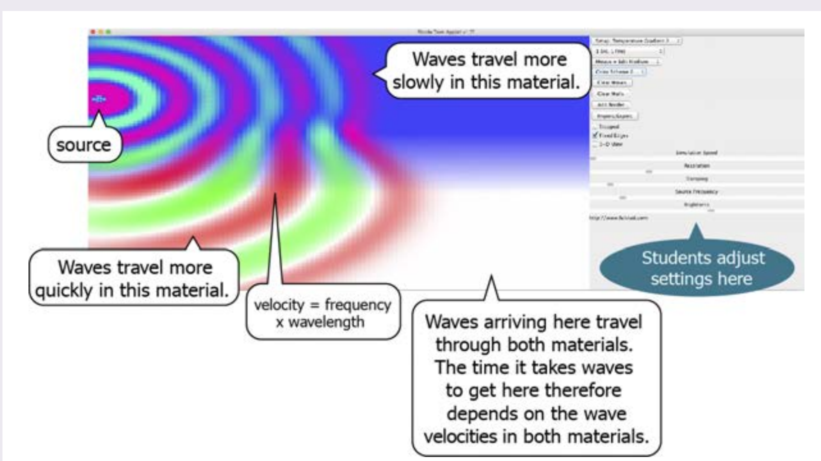


Diagram by M. d'Alessio

Long description of Figure 7.60.

PHYSICS IN THE UNIVERSE VIGNETTE 7.3: SEISMIC WAVES

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

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

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

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

PHYSICS IN THE UNIVERSE VIGNETTE 7.3:
SEISMIC WAVES

Vignette Debrief

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

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

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

PHYSICS IN THE UNIVERSE VIGNETTE 7.3: SEISMIC WAVES

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

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

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

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

Resources

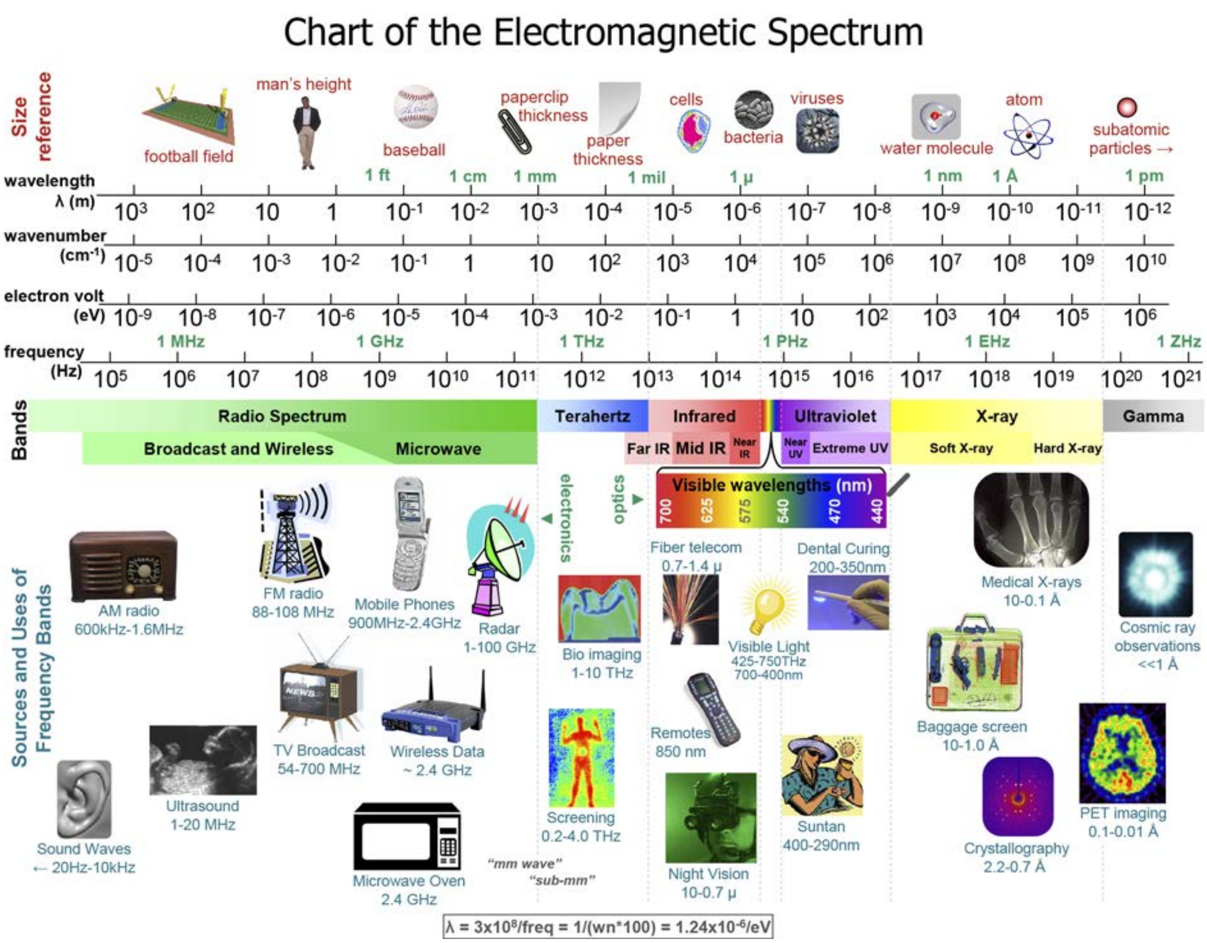
California State University Northridge. n.d. Earthquake Early Warning Simulator. https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link65.

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

The Nature of Light

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

Figure 7.61. The Electromagnetic Spectrum



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

Long description of Figure 7.61.

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

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

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

Waves and Technology

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

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

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

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

IS6

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

According to 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. Other concepts are practical, such as understanding how short-term changes in the behavior of our [S]un 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 stars are made 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 do the following:

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 matter in 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).]

PHYSICS IN THE UNIVERSE INSTRUCTIONAL SEGMENT 6: STARS AND THE ORIGINS OF THE UNIVERSE

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-2] Developing and Using Models [SEP-6] Constructing Explanations (for science) and Designing Solutions (for engineering) [SEP-8] Obtaining, Evaluating, and Communicating Information	ESS1.A: The Universe and Its Stars PS3.D: Energy in Chemical Processes and Everyday Life PS4.B Electromagnetic Radiation	[CCC-3] Scale, Proportion, and Quantity [CCC-5] Energy and Matter: Flows, Cycles, and Conservation

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

CA CCSS for ELA/Literacy Connections: SL.11–12.4; RST.11–12.1; WHST.9–12.2.a–e

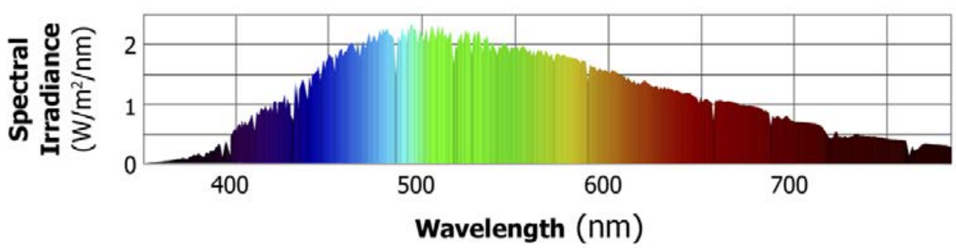
CA ELD Connections: ELD.PI.11–12.1, 5, 6a–b, 9, 10, 11a

Students now apply their understanding of electromagnetic radiation to studying the light from stars. Teachers can start this instructional segment the same way humans have for millennia by 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/Sky Server at SDSS DR12 Navigate Tool, https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link68) 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/Sky Server, "What is Color" at https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link69) and **interpret [SEP-4]** the data by comparing and noting several important **patterns [CCC-1]**. These patterns give clues about the **cause [CCC-2]** of different phenomena.

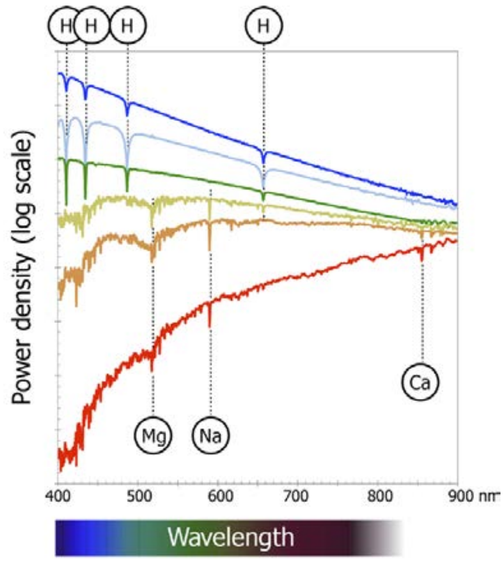
Figure 7.62. Color Spectrum of Our Sun



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. Graph by M. d'Alessio
Long description of Figure 7.62.

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

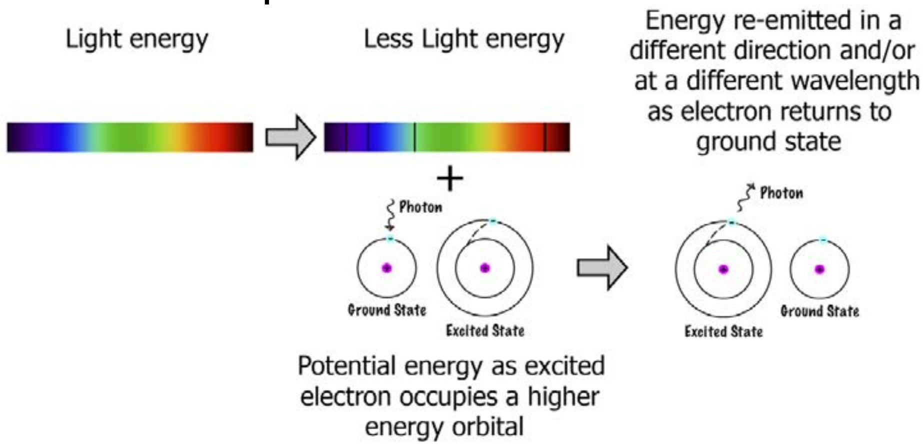
Figure 7.63. Spectra of Six Different Stars



Circles indicate spectral lines from different elements on the periodic table. Graph by M. d'Alessio with data from Sloan Digital Sky Survey/Sky Server n.d.
Long description of Figure 7.63.

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 discover 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 are presented with a 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, stable ground state and temporarily store the energy as a potential energy. The atom quickly converts the energy back to light energy as it returns 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. 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
Long description of Figure 7.64.

The absorption of specific wavelengths of electromagnetic waves occurs in stars, but also all around on Earth, including in greenhouse gases in Earth's atmosphere. Materials like CO_2 and water vapor absorb infrared energy leaving the planet and re-emit it back toward Earth so that energy that would 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, which was 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, their nuclei may get close enough together so that when they collide, 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 biographies about or autobiographies/memoirs by famous or influential scientists known for their 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.) Citing evidence from text, students write a letter to the scientist asking a relevant question about their work. The letter should include a critical concept, knowledge, or discovery by the scientist and identify key ideas, words, and phrases relevant to the topic.

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

CA ELD Standards: ELD.PI. 9–10

A Model of Fusion in Stars Over Their Lifecycle

For fusion to occur, atoms must reach a high enough temperature that they move quickly 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.

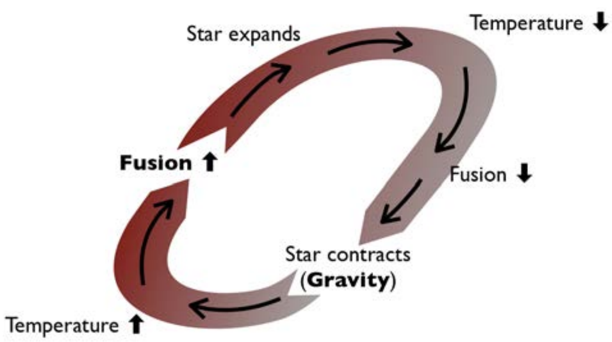
Stellar Birth and Activating Fusion

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 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[10] 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.

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
[Long description of Figure 7.65.](#)

10. 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.

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 hotter, and all stars eventually fuse all the hydrogen in their core to form helium. At that time, 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 (surrounding gaseous material) 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 become 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

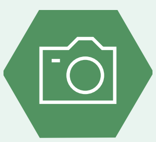
Once hydrogen fusion stops in the Sun's core, hydrogen fusion in its envelope will cause it to grow to be a giant star. Eventually its envelope will expand, leaving behind a core made primarily of carbon and oxygen. That core will still be incredibly hot and it will continue to glow for a long time even 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 with only 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 heavier 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 once 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?"

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 reviewed a table of a number of properties of the 100 nearest stars and the 100 brightest stars using a spreadsheet (figure 7.66). They constructed graphs of different properties looking for **patterns [CCC-1]** in the data. They found that many of the factors were uncorrelated. For example, they probably noticed that bright stars are located both near and far from Earth, but they should have seen a definite pattern between brightness and temperature—hotter stars are brighter and colder stars are dimmer. They may have begun with a linear **scale [CCC-3]**, but with such a large range in the brightness of stars (less than 1 percent as bright up to 100 times brighter than the Sun), they discovered the need to adjust to a logarithmic **scale [CCC-3]**.

Figure 7.66: How Does Star Brightness Depend on Temperature?

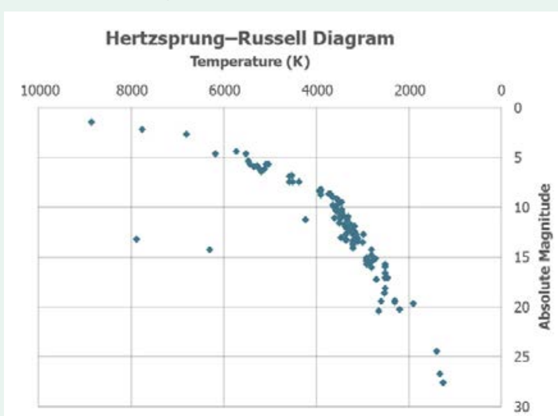


Diagram by M. d'Alessio

Long description of Figure 7.66.

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

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.”

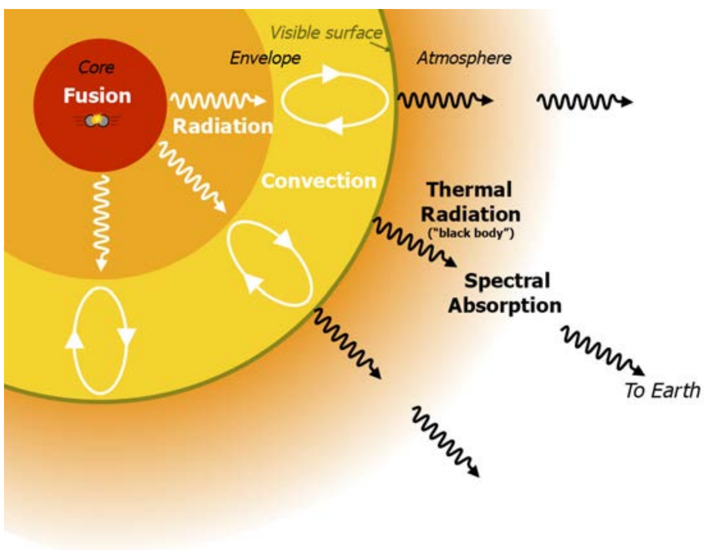
Students **asked questions [SEP-1]** that led them to further investigation. The example student dialog is idealized, but effective talk moves can help structure conversations so that students move towards this ideal (as outlined in the “Instructional Strategies” chapter of this framework).

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 (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 plot along the central diagonal line in the H-R diagram, which is referred to as the *main sequence*. As each star moves through its life cycle and stops fusing elements in its core, it plots in a different section of the H-R diagram than it did during its main sequence.

Getting Energy to Earth

As early as grade five in the CA NGSS, students generated 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 in the middle grades (MS-ESS2-6) and in Earth’s interior in the high school Chemistry in the Earth System course. Now they can apply that model 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 resemble 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
Long description of Figure 7.67.

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. 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 performance expectations. When stars move toward 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 toward 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 have a smaller Doppler shift 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 toward longer wavelengths, revealing that the stars 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 *redshift*.

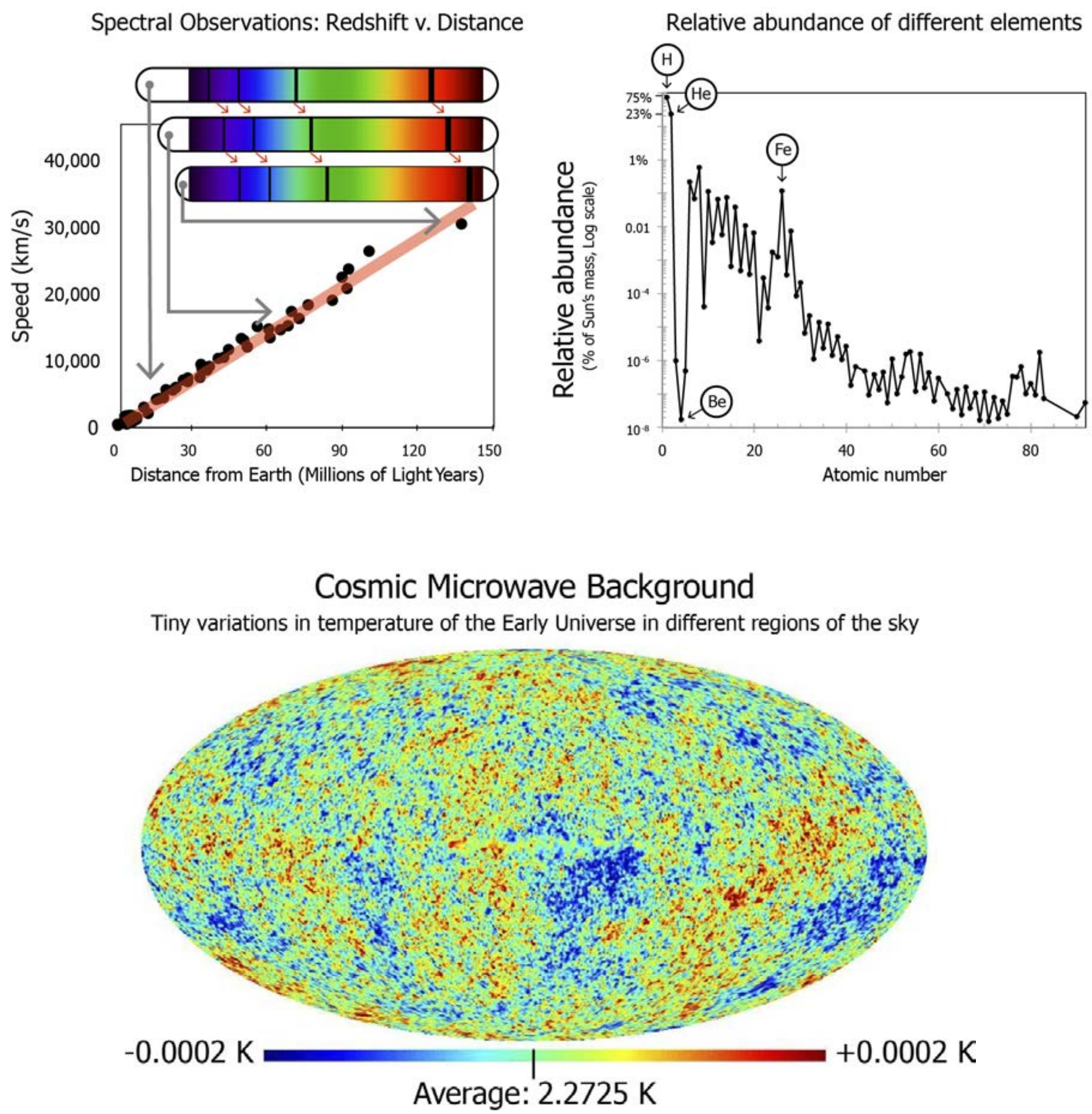
Students are now ready to **obtain information [SEP-8]** from media about Edwin Hubble's surprising discovery that the universe is expanding (see Sloan Digital Sky Survey/Sky Server, The Expanding Universe at https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link70). At the time, scientists wondered if our universe 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 redshift 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 farther 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 https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link71 or University of Washington Astronomy Department at https://www.cde.ca.gov/ci/sc/cf/ch7.asp#link72. This 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' findings 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?" The inevitable answer is that everything that we can see as far as we can look out into the universe was at one time all contained in a tiny region smaller than the size of an atomic nucleus. This region was extremely hot and dense at this time until everything started rapidly to spread apart in what we call the Big Bang. We can see evidence of this expansion in the **matter and energy [CCC-5]** that exists in the universe today. As the material spread apart, it started to cool enough for atomic nuclei to form, but calculations by scientists show that only specific elements would form and in specific proportions. We can look for that "fingerprint" by using spectral lines and other techniques 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 was 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 toward Earth in every direction. They were worried something was 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 toward Earth today. We now call that **energy [CCC-5]** the Cosmic Microwave Background Radiation and can use it to describe 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

[Long description of Figure 7.68.](#)

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