Chapter 7
High School Three Course Model

2016 Science Framework
for California Public Schools
Kindergarten through Grade 12

Chapter 7

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 Next Generation Science Standards for California Public Schools, Kindergarten Through Grade Twelve (CA NGSS), aided by the *Science Framework for California Public Schools: Kindergarten Through Grade Twelve* (*CA Science Framework*), are the first step toward translating that vision into practice.

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

Overall High School Three-course Model Introduction

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

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

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

Organization Within Courses

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

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

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

Essential Shifts in the CA NGSS

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

All Standards, All Students

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

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

Course Sequencing Discussion

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

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

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

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

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

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

Living Earth Early or Late in the Sequence?

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

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

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

Physics of the Universe Early or Late in the Sequence?

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

Credential Information

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

Chemistry in the Earth System:

Integrating Chemistry and Earth & 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 away. 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, looking 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 Next Generation Science Standards for California Public Schools, Grades Kindergarten Through Grade Twelve (CA NGSS). Districts should be mindful and be sure to allocate resources to professional development and collaborative planning time so that teachers can learn from one another. No matter what resources are allocated, teachers will still have to choose how to react to the **change [CCC-7].**

Purpose and Limitations of this Example Course

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

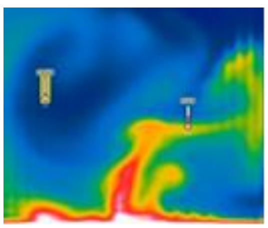
This example course is divided into instructional segments (IS) centered on questions about observations of a specific phenomenon. Different phenomena require different amounts of investigation to explore and understand, so each IS should take a different fraction of the school year. As students achieve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

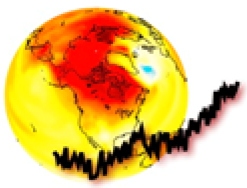
This chapter clarifies the general level of understanding required to meet each PE, but the exact depth of understanding expected of students depends on this course's place in the overall high school sequence. Teachers could modify the content and complexity so that the course serves as a basic freshman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

Example Course Mapping for an integrated 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 (IS) 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 its reaction product, 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 due to 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.

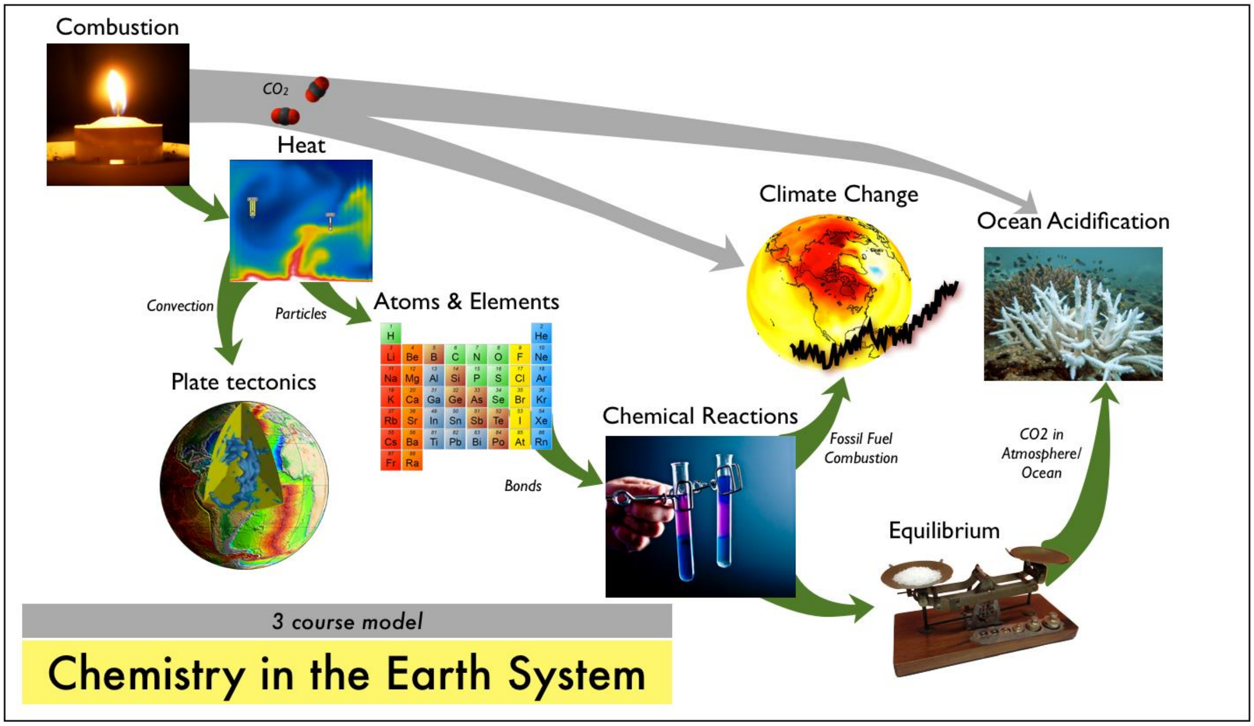
Table 7.4. Overview of Instructional Segments for High School Chemistry in the Earth System

	***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 in 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; Rotard and Ertl 2005; Amitchell125 2011; Geophysical Fluid Dynamics Laboratory 2007; Acropora 2011; A.M. Lebow.

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



Sources: Giardino 2006; M. d'Alessio; National Oceanic and Atmospheric Administration, National Centers for Environmental Information 2008b; NASA/Goddard Space Flight Center Scientific Visualization Studio 2002; Rotard and Ertl 2005; Amitchell125 2011; Geophysical Fluid Dynamics Laboratory 2007; Acropora 2011; A.M. Lebow.

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 IS, students **investigate [SEP-3]** a simple chemical system and begin to **ask questions [SEP-1]** about it. This IS lays the foundation for achieving several PE's but is not designed in a way that students fully meet any of them upon completion. The IS is instead here 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: 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 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 IS6. Revisited in IS7.)**

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-1] Asking Questions and Defining Problems **[SEP-2] Developing and Using Models** **[SEP-4] Analyzing and Interpreting Data**	**PS1.A: Structure and Properties of Matter** **PS1.B: Chemical Reactions** **PS3.D: Energy and Chemical Processes in Everyday Life**	**[CCC-1] Patterns** **[CCC-2] Cause and Effect** **[CCC-4] System and System Models** **[CCC-5] Energy and Matter: Flows, Cycles, and Conservation** **[CCC-7] Stability and Change**

CA CCSS Math Connections: MP.4; N-Q.1-3;
CA ELD Connections: ELD.PI.11-12.1,5,6a-b,9,10,11a
CA CCSS ELA/Literacy Connections: SL.11-12.5; RST.11-12.1; WHST.9-12.7,8,9

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 are Calories?" and "how do they measure them?" 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[1] 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 larger the change in food mass, the higher 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 fifth grade, 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]** that they defined because the products of combustion are hot gases and not because they disappeared

[1] 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.

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 such as the original soda that was 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, and then monitoring the temperature **change [CCC-7]** over time both while the nut is burning and afterwards as 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 is the difference 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).

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: 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-PS3-4. 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**	**PS3.A: Definitions of Energy** **PS3.B: Conservation of Energy and Energy Transfer**	**[CCC-1] Patterns** **[CCC-2] Cause and Effect**

Investigations **[SEP-5] Using mathematics and Computational Thinking** **[SEP-6] Constructing Explanations (for science) and Designing Solutions (for engineering)** **[SEP-7] Engaging in Argument from Evidence** **[SEP-8] Obtaining, Evaluating, and Communicating Information**	**ESS2.B: Plate Tectonics and Large-Scale System Interactions**	**[CCC-3] Scale, Proportion, and Quantity** **[CCC-5] Energy and Matter: Flows, Cycles, and Conservation** **[CCC-7] Stability and Change**
CA CCSS Math Connections: N-Q.1-3; MP.2; MP.4		
CA ELD Connections: ELD.PI.11-12.1,5,6a-b,9,10,11a		
CA CCSS ELA/Literacy Connections: SL.11-12.4,5; RST.11-12.1,2,8, WHST.9-12.7,8,9		

Energy [CCC-5] is perhaps the most unifying CCC 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 whose velocity 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 middle grades claim 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).

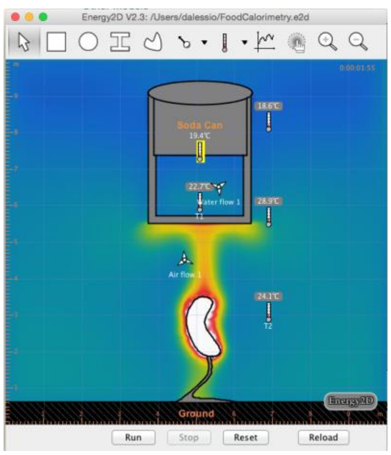
The Second Law of Thermodynamics defines the conditions under which **energy will flow [CCC-5]** between components in a system. Isolated systems always progress toward thermodynamic equilibrium with maximum entropy. In other words, systems strive towards a uniform energy distribution among all the components. 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 the instructional strategies chapter of this framework (and would definitely meet this PE). 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 Physics of the Universe course. Online simulations allow students to visualize each of these processes at the microscopic **scale [CCC-3]** (see https://phet.colorado.edu/en/simulations/category/physics/heat-and-thermodynamics).

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 http://energy.concord.org/energy2d/). 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 in 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.

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 more dense. 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 at the middle grade level (*MS-ESS2-6*), and now they extend it to processes inside the Earth.

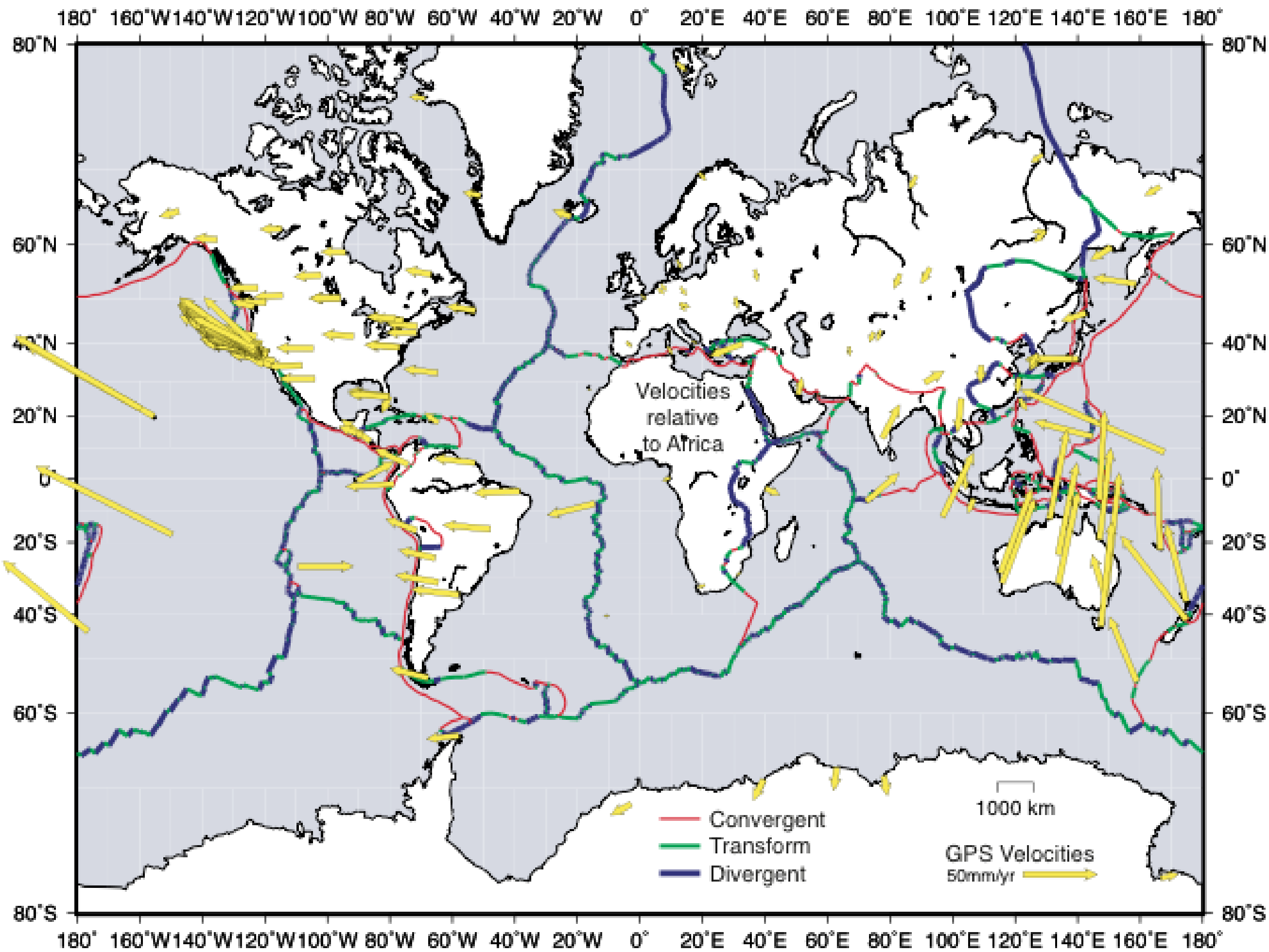
Students must **develop a model [SEP-2]** of Earth's interior and use evidence to **support the claim [SEP-7]** that its interior is convecting. Lava lamps are not perfect **models [SEP-2]** of convection in Earth's interior because there is strong evidence from seismic waves that most of the interior is not a liquid. One type of seismic waves 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 at https://www.iris.edu/hq/inclass/lesson/determining_and_measuring_earths_layered_interior). 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 they may have discussed at the middle grade level (*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. Silly 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 silly putty. The fact that categories students have used to describe the phases of matter fails 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 12th grade 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. These huge sections of lithosphere that are dragged along as a single chunk are what we call plates, and their movement 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 1980's, 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 and then 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

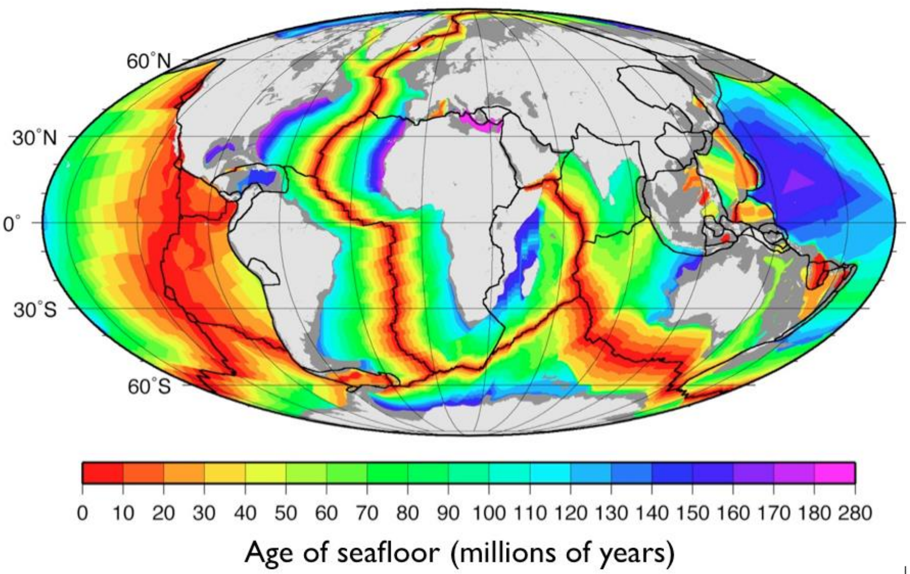


Velocites from U.C. Berkeley's BAVU1.01, 2004. Shown relative to stable Nubia as defined by Kreemer, 2003. Plate Boundaries from Peter Bird, UCLA 2003. Compiled by M. d'Alessio, U.C. Berkeley under the DLESE CA Pilot Project.

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.

The mechanism causing new seafloor to form is another example of a density-driven flow. When two plates move apart from one another, the release of pressure allows solid material expand slightly causing decompression melting. The melted magma is less dense than the surrounding solid rock, so it quickly rises up and forms new sections of lithosphere. As the plates continue to move, this rock gets older and is dragged farther 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 2008a

This section on heat flow within the Earth illustrates how studying ESS and PS 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). Students' understanding of PS benefits because studying the role of convection in the Earth 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 ESS benefits because they develop models that relate the driving forces of plate motions to **energy flow [CCC-5]**. 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.

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

The previous IS examined the thermal interactions of objects by looking at the **energy [CCC-5]** of microscopic particles that make them up. 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 fifth grade that objects are made of particles too small to be seen (*5-PS1-1*), modified slightly by the middle grade level where they defined some particles as molecules that are made of groups of atoms held together in simple structures (*MS-PS1-1*). This IS 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: 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)**

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

Highlighted Science and Engineering Practices	Highlighted Disciplinary Core Ideas	Highlighted Crosscutting Concepts
[SEP-1] Asking Questions and Defining Problems	**PS1.A: Structure and Properties of matter**	**[CCC-1] Patterns** **[CCC-2] Cause and**

[SEP-2] Developing and Using Models **[SEP-3] Planning and Carrying Out Investigations** **[SEP-4] Analyzing and Interpreting Data** **[SEP-5] Using Mathematics and Computational Thinking** **[SEP-6] Constructing Explanations (for science) and Designing Solutions (for engineering)** **[SEP-7] Engaging in Argument from Evidence** **[SEP-8] Obtaining,**	**PS1.B: Chemical Reactions** **PS2.B: Types of Interactions**	**Effect** **[CCC-3] Scale, Proportion, and Quantity** **[CCC-5] Energy and Matter: Flows, Cycles, and Conservation**

Evaluating, and Communicating Information]		
CA CCSS Math Connections: N-Q.1-3; MP.2;		
CA ELD Connections: ELD.PI.11-12.1,5,6a-b,9,10,11a		
CA CCSS ELA/Literacy Connections: SL.11-12.4; RST.9-10.7, WHST.11-12.2,5		

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* states that:

> 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)

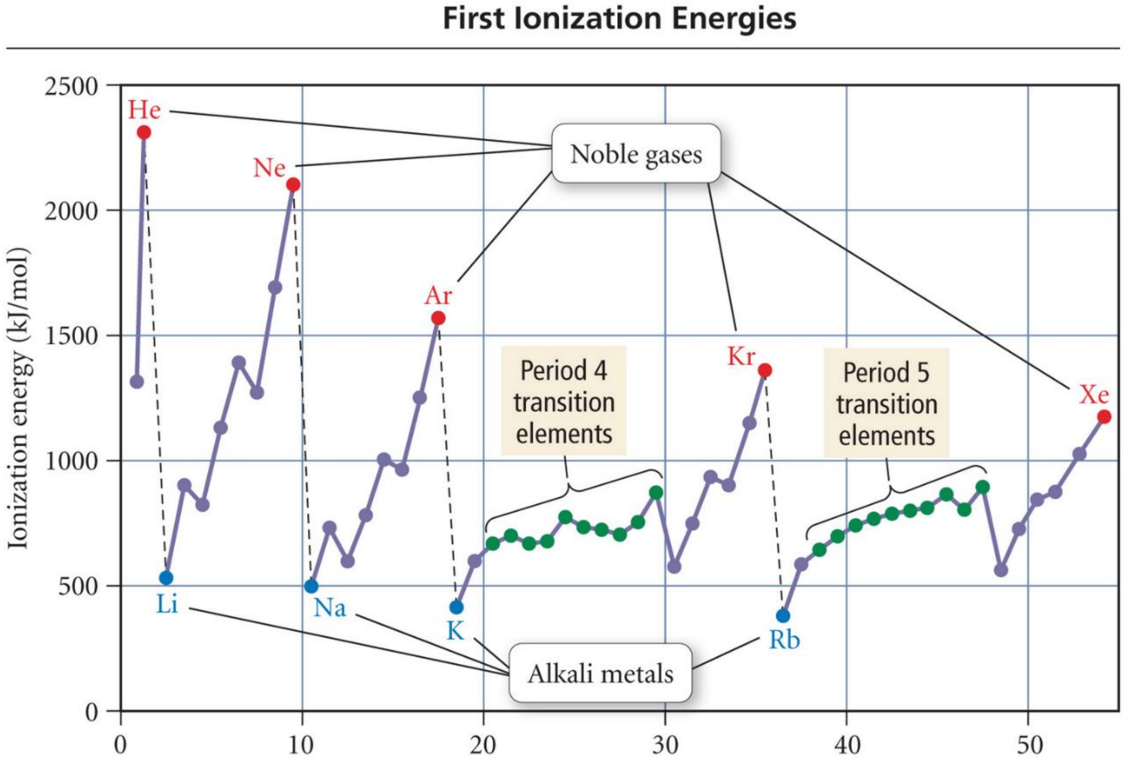
The PEs in middle school do not require students to develop a model of the atom's internal workings, This sequence differs from the 1998 California Science Content Standards where the internal workings of the atom were introduced in eighth grade, and it is conceivable that students highly proficient in the CA NGSS PEs for middle school 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 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 'periodic' way, and arranged the 63 known elements 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. They arrange 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, mirroring the process Mendeleev used to predict the existence of elements not yet known.

Patterns [CCC-1] are a key CCC 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 gasses 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 IS. 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

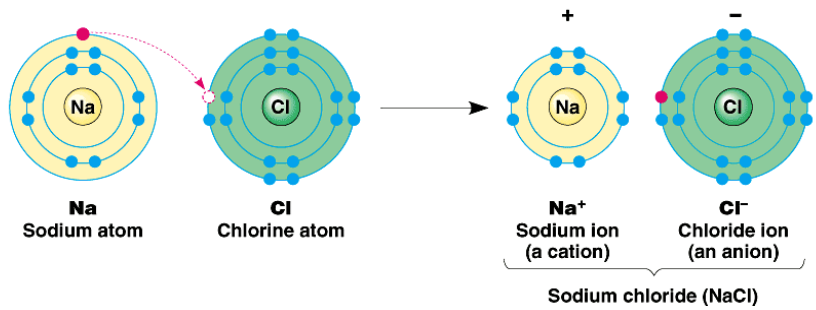


As students analyze plots of the properties of the elements as a function of atomic number, they should notice and discuss trends and patterns such as the comparatively low ionization energies of the alkali metals versus the high ionization energies of the noble gasses as seen in this plot of first ionization energies. Source: Tro 2008, chapter 8.

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 model 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 parallel's the learning progression outlined in the CA NGSS where 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 PEs in the CA NGSS.). Students can make these models 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 on 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

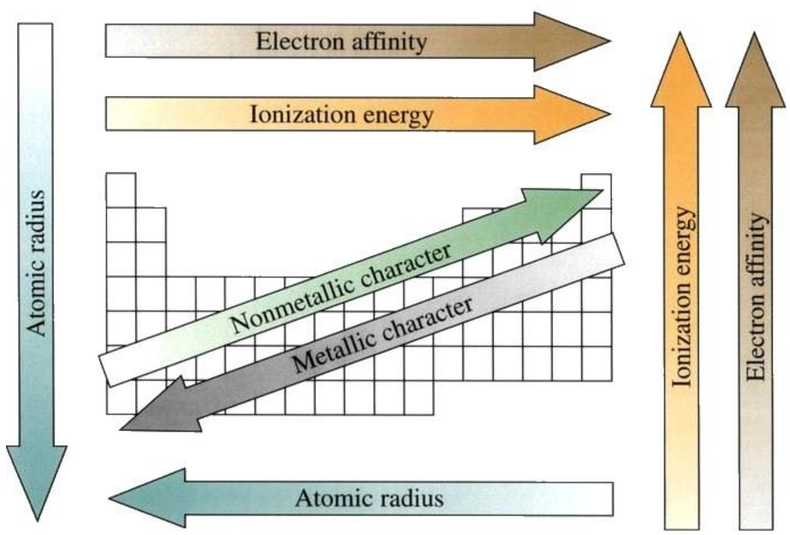


Students should predict trends within the periodic table based upon an application of models of atomic structure such as the Bohr model and octet rule illustrated here. Source: Meddic 2015.

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 PE, 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 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 exist, and be able to explain (**cause and effect [CCC-2]**) 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 fourth 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: Texas A&M University, Department of Chemistry 2014.

Cycles of Matter in Chemical Reactions

As students study these simple combinations of atoms to 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.

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: 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.]** 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-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-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)**

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)**	**PS1.B: Chemical reactions** **ETS1.C: Optimizing the Design Solution**	**[CCC-1] Patterns** **[CCC-2] Cause and Effect** **[CCC-5] Energy and Matter: Flows, Cycles, and Conservation** **[CCC-7] Stability and Change**
CA CCSS Math Connections: A-SSE.1a-b, 3a-c; N-Q.1-3; MP.2; MP.4		
CA ELD Connections: ELD.PI.11-12.1,5,6a-b,9,10,11a		
CA CCSS ELA/Literacy Connections: SL.11-12.5; RST.11-12.1, WHST.11-12. 7,8,9		

Students were introduced to chemical reactions in the middle grades. In particular, they learned that “substances react chemically in characteristic ways”, and that “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 have 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 IS, 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).

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 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.

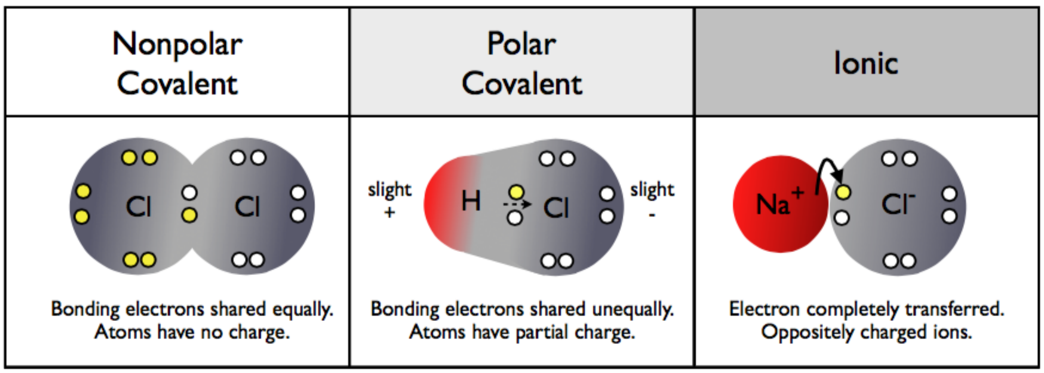
Observations at the macroscopic level give clues about the nature of chemical bonding (HS-PS1-3). When students **conduct an investigation [SEP-3]** to measure the conductivity of different solutions (salts, acids, bases, hydrocarbons, and oxides), they gather evidence that there must be some relationship 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 nucleus of one atom has enough attractive force to pull one, two, or three electrons away from nuclei 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



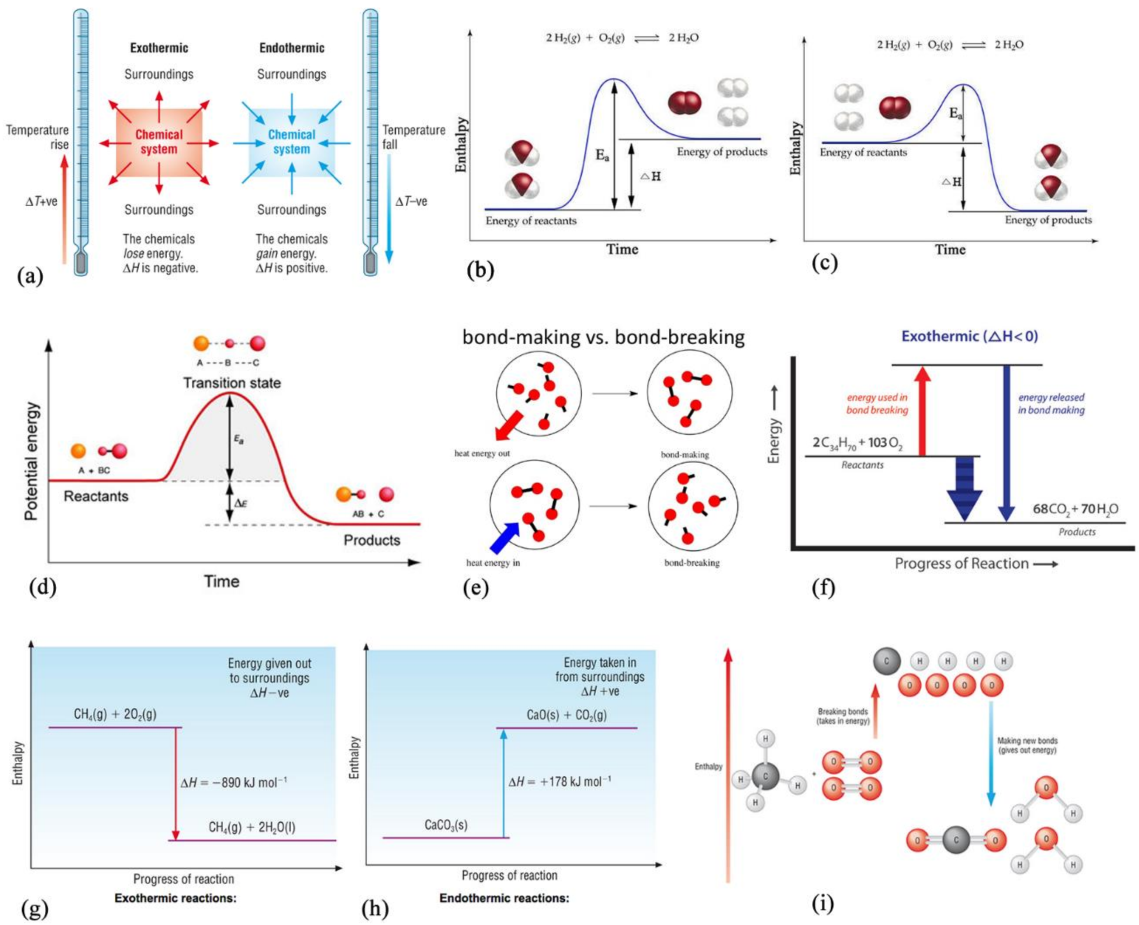
Students should be able to develop and explain models of covalent, polar covalent, and ionic bonding.

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.

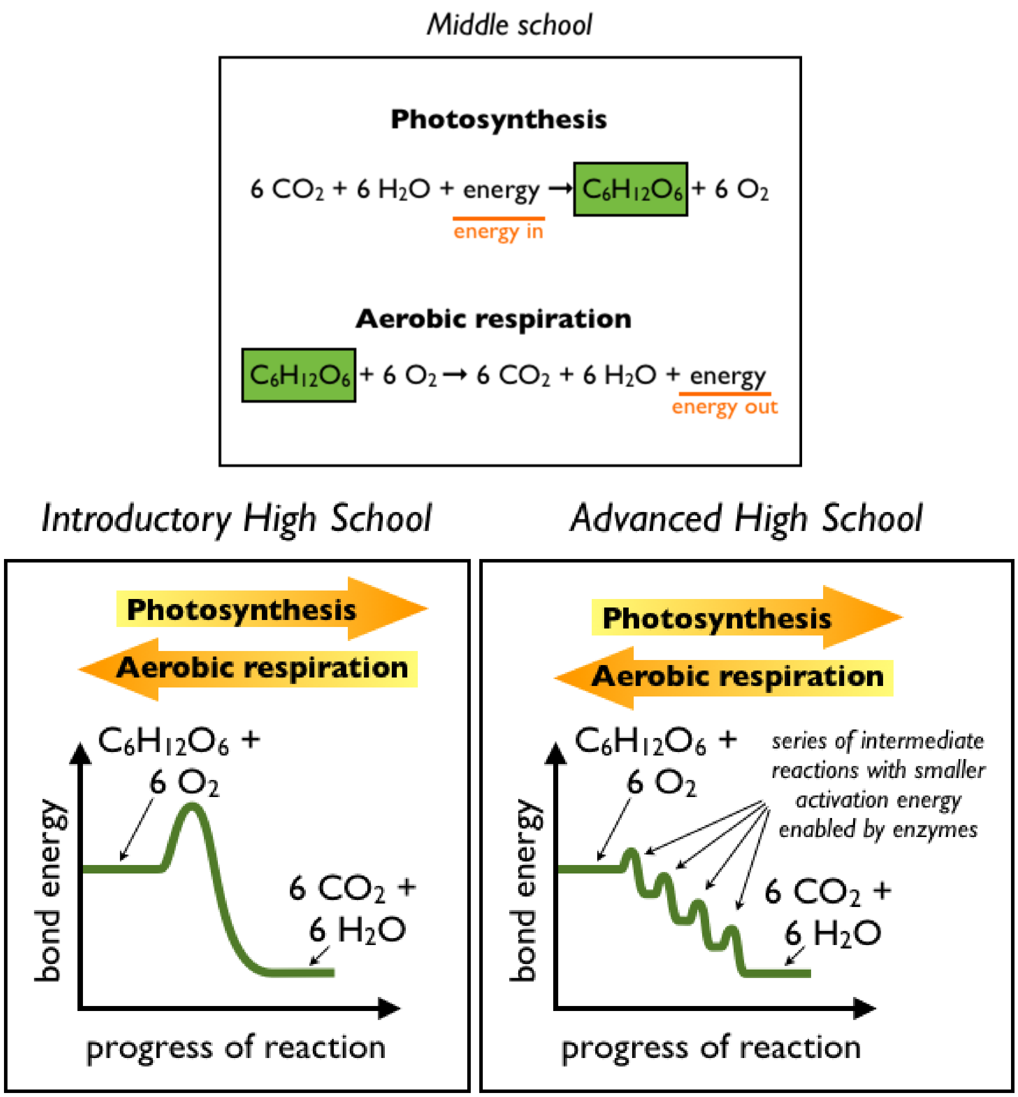
Figure 7.27. Models of Energy Changes in Chemical Reactions



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. Sources: a, g, h, i: A Level Chemistry 2015; b, c: Birdville Independent School District 2015.

In students' **model [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 can now can be understood in greater detail given 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 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 (top; 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 (bottom left). 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.

High School Chemistry Snapshot 7.7. Chemical Energetics
Both CA NGSS and the 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 realizes that his chemistry students often memorize 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 develops a two-day lesson about modeling the energy in chemical bonds (HS-PS1-4) as part of a larger IS on chemical reactions. At the beginning of class, Mr. S distributes reusable hot and cold packs, used to treat sports injuries, and instructs 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 change in a collaborative online database. Despite variations in individual recordings among classmates, students notice similar **patterns [CCC-1]** in the temperature gains or losses for the hot and cold packs. 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. writes the words "endothermic" and "exothermic" on the board and asks students to enter as many words as they can 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 has grown to several dozen words, including: *exit, extinct, exotic, exoskeleton, exocrine, extraterrestrial, endemic, endocrine, endosperm; and thermometer, thermistor, thermophilic, thermoregulation.* Mr. S then prompts his students to predict the meaning of these roots based upon the meanings shared by the words that contain them. Mr. S monitors their predictions as they enter them in an online input form and calls upon students whose digital responses demonstrate understanding and who have not shared with the class recently. He asks 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 asks students to identify the hot and cold pack reactions as being either *endothermic* or *exothermic*, and once again assesses their responses from the online form.

Confident that his students have an intuitive understanding of exothermic and endothermic reactions as well as the vocabulary to describe these reactions, Mr. S projects a slide comparing several different annotated graphs (figure 7.27) and says, "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 assesses the ability of his class to observe salient patterns, and notices that the majority have noted that multiple drawings include 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 selects Isabella, a student who has not had an opportunity to share in the last few days, to explain her observations. Isabella is confident that she has something significant to share, because she knows that Mr. S pre-screens student responses in the cloud and only calls on students who have demonstrated that they have something worthy of sharing. Isabella comments on the similarities and differences between the diagrams and explains that the model in the upper left may represent the heat pack while one next to it may represent the cold pack. Mr. S asks her to provide evidence to support her **argument [SEP-7]**, which she does. Mr. S then asks other students to share their observations and concludes by emphasizing that there are multiple ways to model or represent natural phenomena, and that each has its strengths and weaknesses. He then emphasizes 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 emphasizes 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 assigns as homework an online quiz that assesses student understanding of each type of model.

Investigative phenomenon: Different chemical reactions produce different temperature changes.

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

(1) $CaO(s) + H_2O(l) \longrightarrow Ca(OH)_2(s)$ (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 & 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 take screen captures of the temperature plots, classify each reaction as endothermic or exothermic, and represent it using two or more of the model-types shown in figure 7.27, or an additional model type that they develop on their own. When writing their lab reports, students apply scientific principles and evidence to **construct explanations [SEP-6]** for the thermal **changes [CCC-7]** that they have 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.

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

In this IS, 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). The IS focuses on the natural cycle of carbon and human impacts on it (CA EP&Cs III, IV). Since the carbon cycle is intricately linked to all life on Earth, the IS integrates with life science units where 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: **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.] **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.

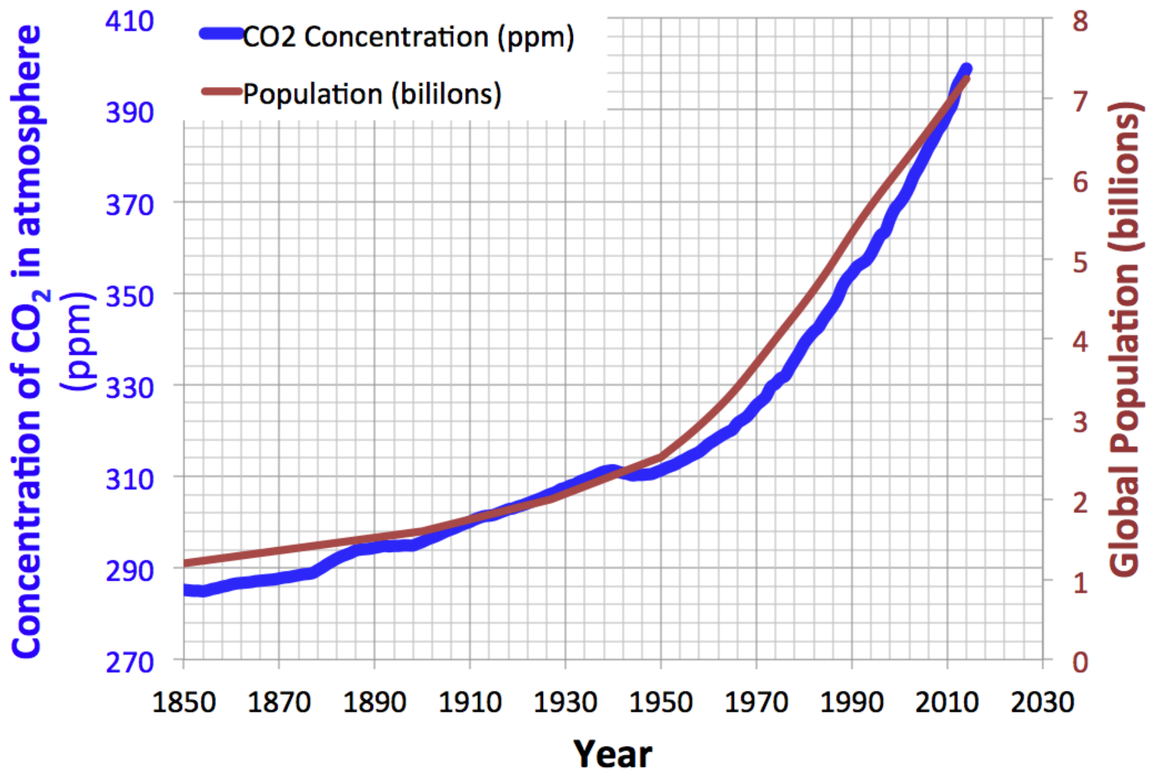
The bundle of performance expectations above focuses on the following elements from the NRC document *A Framework for K–12 Science Education*:		
Highlighted Science and Engineering Practices	**Highlighted Disciplinary Core Ideas**	**Highlighted Crosscutting Concepts**
[SEP-1] Asking Questions and Defining Problems **[SEP-2] Developing and Using Models** **[SEP-3] Planning and Carrying Out Investigations** **[SEP-4] Analyzing and Interpreting Data** **[SEP-5] Using Mathematics and Computational Thinking**	**PS3.B: Conservation of Energy and Energy Transfer** **PS3.D: Energy and Chemical Processes in Everyday Life** **PS4.B: Electromagnetic Radiation** **ESS2.A: Earth Materials and Systems** **ESS2.D: Weather and Climate** **ESS3.A: Natural Resources**	**[CCC-1] Patterns** **[CCC-2] Cause and Effect** **[CCC-4] System and System Models** **[CCC-5] Energy and Matter: Flows, Cycles, and Conservation** **[CCC-6] Structure and Function** **[CCC-7] Stability and Change** **Influence of Science,**

[SEP-7] Engaging in Argument from Evidence **[SEP-8] Obtaining, Evaluating, and Communicating Information**	**ESS3.B: Natural Hazards** **ESS3.C: Human Impacts on Earth Systems** **ESS3.D: Global Climate Change** **LS2.B: Cycles of Matter and Energy Transfer in Ecosystems**	**Engineering, and Technology on Society and the Natural World**
Highlighted California Environmental Principles & 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: MP. 1, MP. 2, MP. 3, MP.4; N-Q.1; LE.1b,c; S-ID.6,7		
CA CCSS 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.Ex;		

Students revisit the introductory activity in IS1 on combustion through the lens of their new mental **models [SEP-2]**. Students likely have prior knowledge 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 also 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 we use in everyday life are hydrocarbons, including logs of firewood, natural gas on our stovetops, and the gasoline we put in our cars. All of these hydrocarbons produce carbon dioxide as they provide us the energy we use every day. In fact, as more and more people inhabit the planet, we are emitting more carbon dioxide into the atmosphere every day that accumulates in our atmosphere (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 that raises the concentration of CO_2 in our atmosphere. In recent years, global population is slowing its growth but changes to lifestyles that burn more hydrocarbons for energy are causing emissions to continue to grow. Image Credit: M. d'Alessio using data from NASA n.d.; NOAA 2016a; United Nations, Department of Economic and Social Affairs, Population Division 2015; United States Census Bureau 2016.

The carbon dioxide produced by combustion plays a crucial role in regulating Earth's climate system (CA EP&C IV, see also EEI curriculum unit on the Greenhouse Effect on Natural Systems at http://www.californiaeei.org/curriculum/). In this IS, 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 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; and
- 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 to topics included in IS5, such as greenhouse gases, deforestation, damming rivers, loss of wetlands, or burning fossil fuels. Encourage students to develop and organize 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).

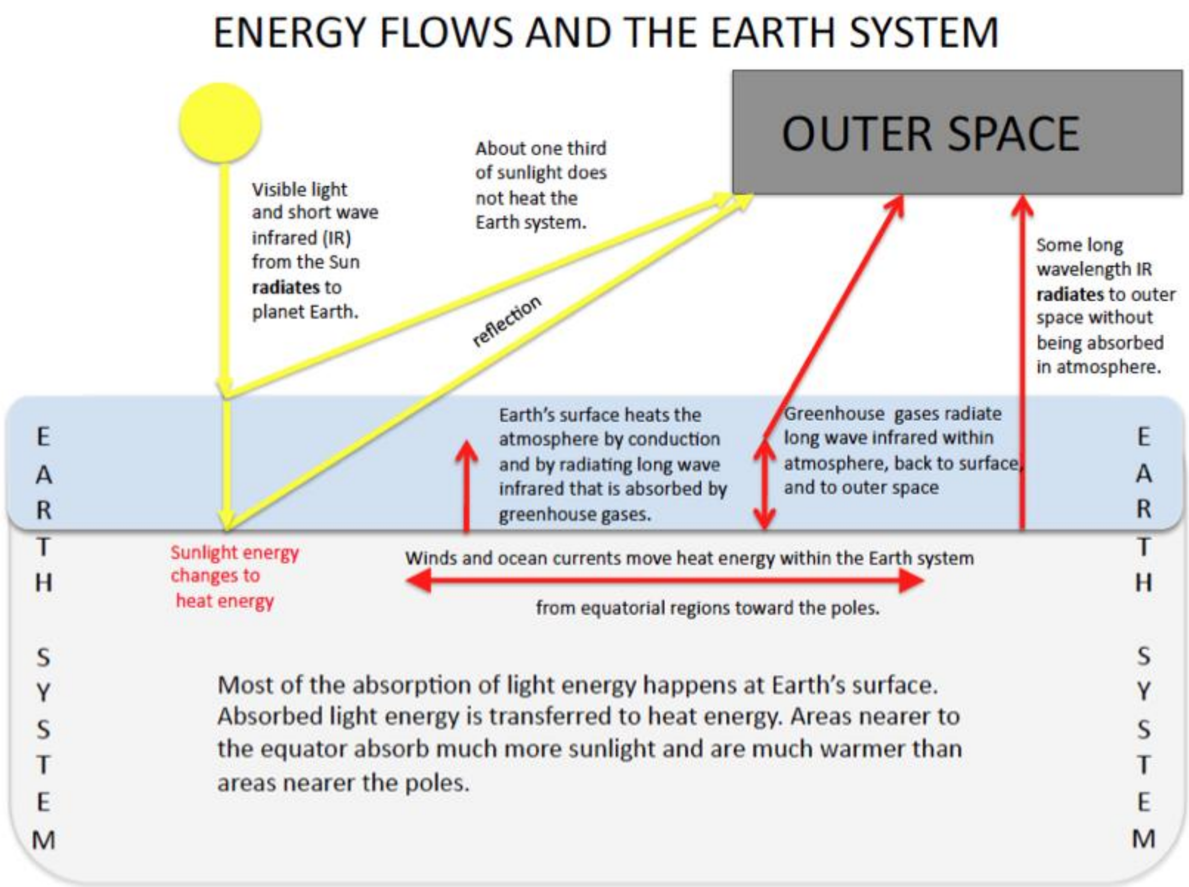
CA CCSS ELA/Literacy Standards: RST.9–12.2, 4, 5

CA ELD Standards: ELD.PI. 9–12.6

The PE's in this IS builds on significant work on DCIs related to weather and climate (*ESS2.D*) in the middle grade standards where 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 IS, 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.

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.

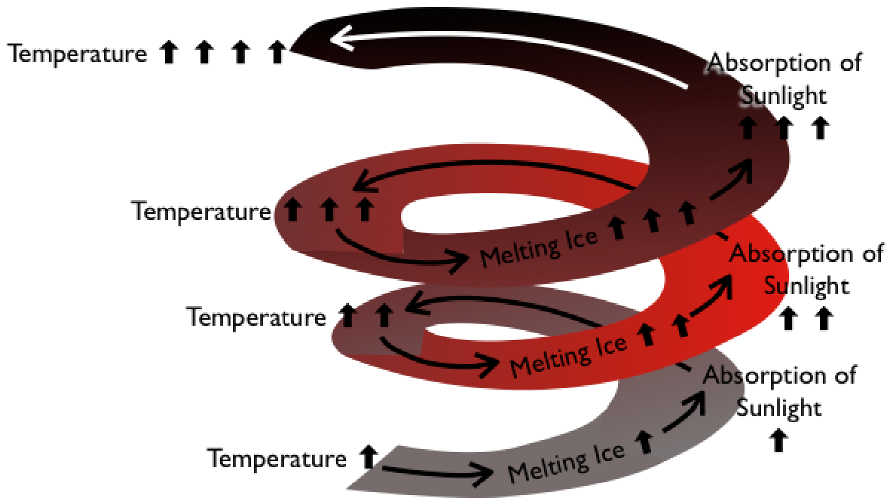
Most of the sunlight that reaches Earth is absorbed and is transformed to thermal **energy [CCC-5]**. If there were no atmosphere to hold that energy, it would radiate right back into space as infrared radiation (like an unpopular amusement park ride where people get on as soon as they arrive because 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's 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 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.

High School 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 "the largest climate disaster in US history."
Motivated by the recent news story about a major methane leak in California, Mr. P's students are **asking questions [SEP-1]** about what *other* gases can trap infrared energy. Mr. P wants his honors chemistry students to develop **models [SEP-2]** of how greenhouse gases absorb infrared energy. They begin with a basic computer simulation (see PhET. "The Greenhouse Effect" at https://phet.colorado.edu/en/simulation/greenhouse) 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 provides 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 has 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 is 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

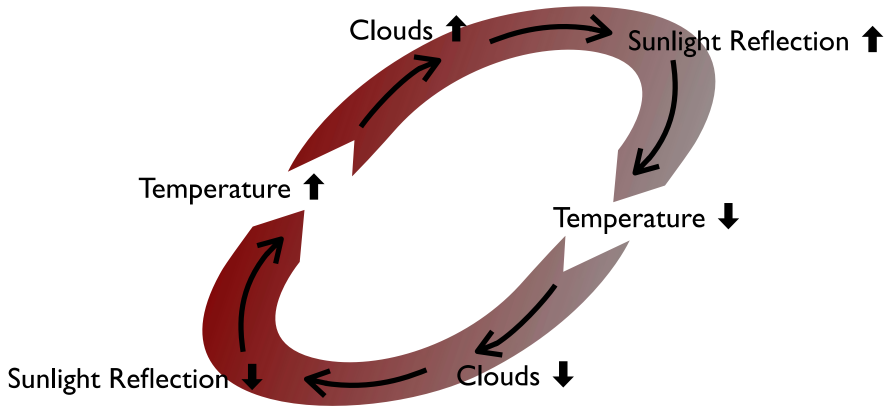


A reinforcing feedback in Earth's climate system. As the planet warms, more ice will melt, which will expose darker ground surfaces that absorb more sunlight, which will in turn make temperatures rise even more. Diagram by M. d'Alessio and A. Sussman.

A counterbalancing feedback loop reduces the amount of change (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[2]. These changes are opposite and can balance each other out.

[2] 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



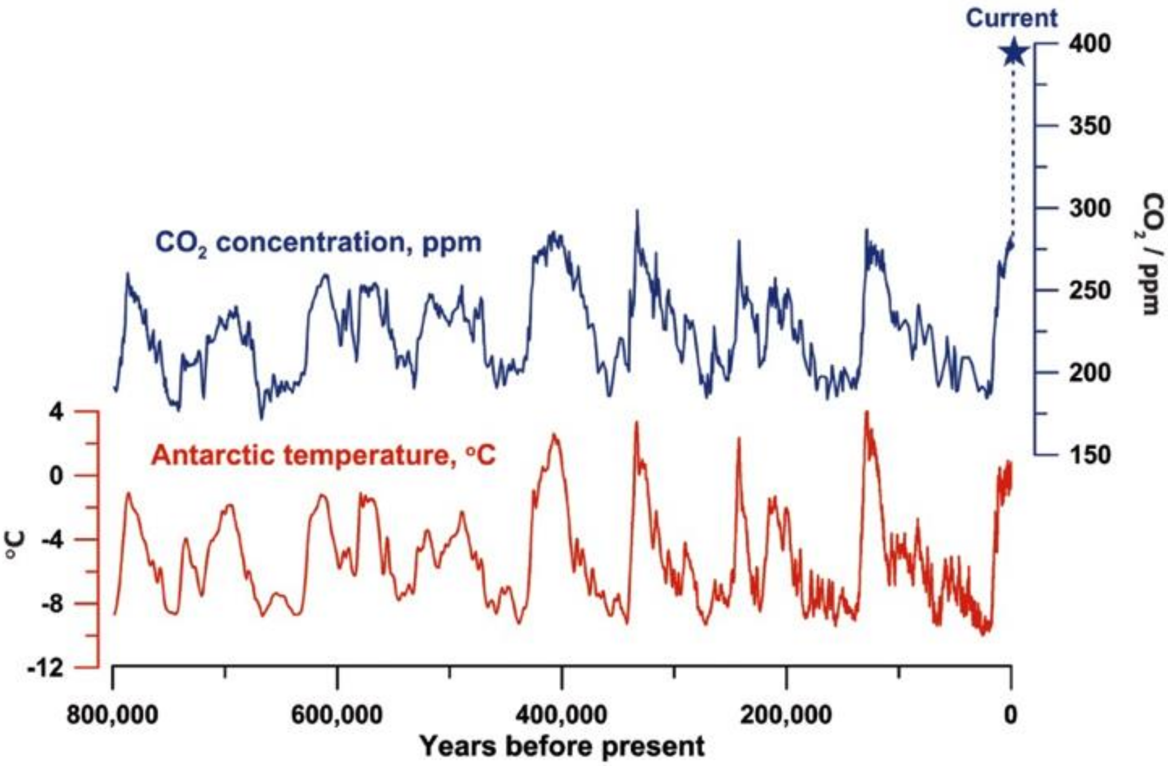
Temperature changes cause changes to the number of clouds because of evaporation. Clouds, in turn, reflect light. Diagram by M. d'Alessio and A. Sussman.

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 can act as tiny time capsules that allow scientists to study actual samples of the ancient atmosphere. Since snow and ice buildup 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.

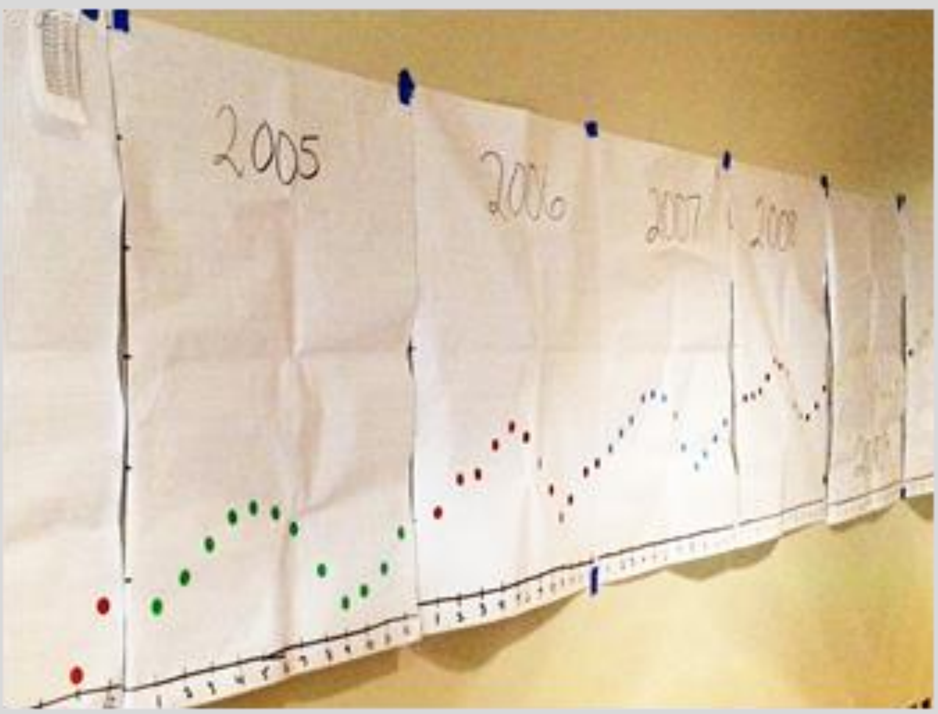
High School Chemistry in the Earth System Snapshot 7.9: Trends and Patterns in Modern Atmospheric CO_2 Levels

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

R wants the students to get a sense for how much CO_2 there is and how it has changed over time. She introduces the units of parts per million (ppm), relating it to the familiar concept of percent (parts per hundred). She also uses her city, which has almost a million people in it, as an analogy where 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 distributes 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 http://www.esrl.noaa.gov/gmd/ccgg/trends/). Each team places stickers to plot data from a different year, but all graph papers have identical axes with identical scales. She asks students to identify trends and **patterns [CCC-1]** they see in their one year of data and almost every group indicates that the graph goes up and down once over the course of the year, with the peak value sometime in the middle of the year. Students associate 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.

The class tapes their graphs side-by-side to the wall in sequence so that they create one long time series graph. Each class period is assigned additional data from different years and by the end of the school day, her classes have filled the entire length of the hallway with 35 years of data (figure 7.34). She shows an interactive visualization of global CO_2 data (see NOAA, History of atmospheric carbon dioxide from 800,000 years ago until January, 2014 at http://www.esrl.noaa.gov/gmd/ccgg/trends/history.html) so that students can observe the trend using a more dynamic visualization, and she asks students to **evaluate [SEP-8]** the benefits of using each format. Ms. R begins the following class period having students walk along the entire graph. She asks 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 has them calculate the year in which atmospheric CO_2 will reach 540 ppm (approximately double the pre-industrial CO_2 levels), assuming that current trends continue. When students compare their predictions, she has them discuss assumptions they made about how quickly the CO_2 would increase (some groups assume a linear increase, while others noticed that the curve seemed to be growing more and more each year). She will relate back to this discussion when the class researches energy resources.

Figure 7.34. Time Series of CO_2 on a Classroom Wall



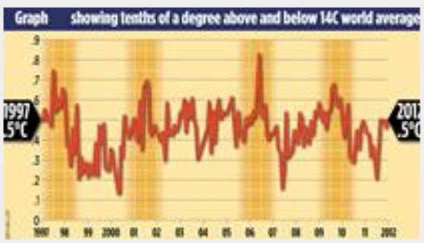
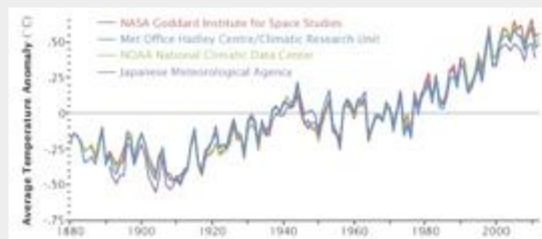
Picture by M. d'Alessio

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 (CA 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.

High School Chemistry in the Earth System Snapshot 7.10: "Dear Editor," 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 http://undsci.berkeley.edu/article/sciencetoolkit_01). She now has them read two internet articles with radically different headlines that each use a graph of global temperature as **evidence [SEP-7]**. Students work in pairs to evaluate the two articles

based on the criteria outlined in the Science Toolkit. Walking around the room, Fernando asks her about the sources: "this article is from NASA, but what is the Daily Mail? Who wrote it?" She encourages him to do a quick internet search about the newspaper's editorial board. A bit later, Cynthia mentions 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*
	
(Rose 2012)	(Simmon 2013)

Ms. Q then asks the whole class to discuss the graphs and construct an **argument [SEP-7]** about which graph contains stronger **evidence [SEP-7]**. Ali notices that one graph includes a much longer span of time, "and climate is supposed to be a long term thing." Jenni says, "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 write letters to the editor in response to the Daily Mail article articulating their **argument [SEP-7].**

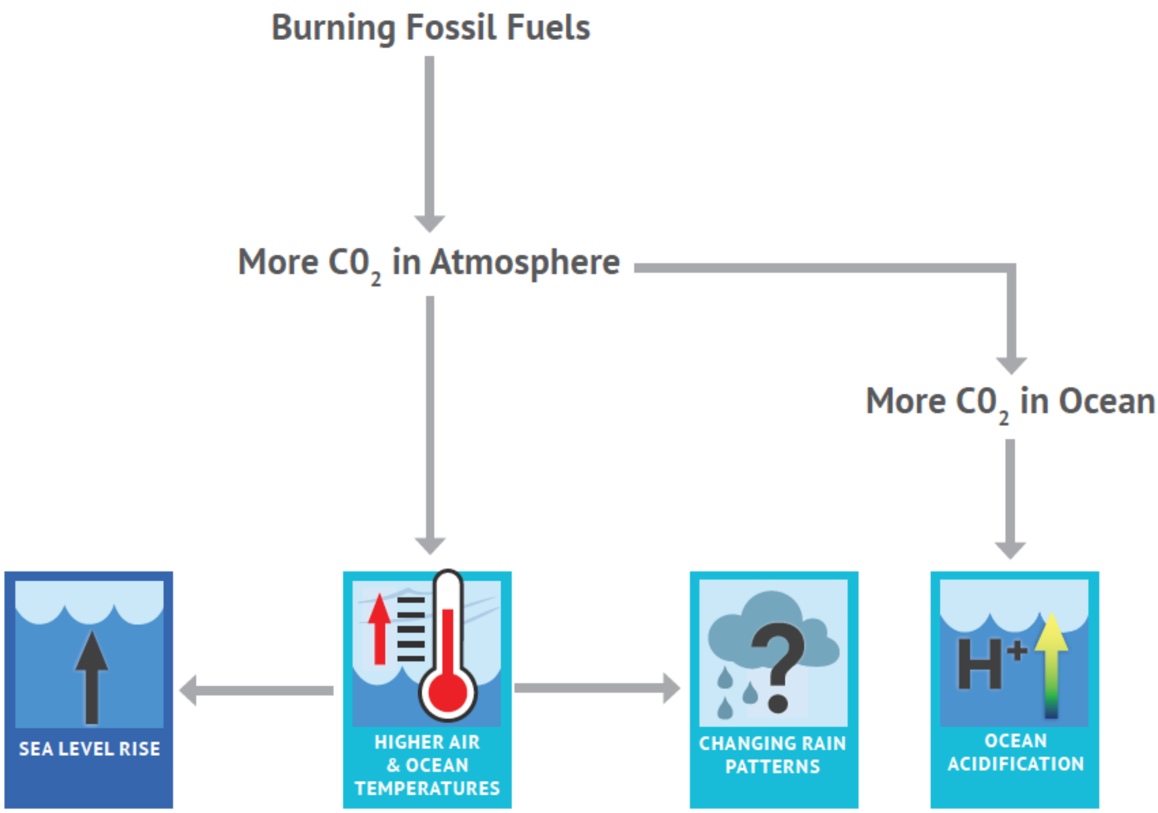
In the CA NGSS, students combine their general understanding with **computational thinking [SEP-5]** by using simple computer simulations (see PhET, The Greenhouse Effect at http://phet.colorado.edu/en/simulation/greenhouse) to model the **flow of energy *[CCC-5]*** into and out of the Earth and the 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]** (GCM's) 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 GCM's exist for educational purposes (see Columbia University, EdGCM at http://edgcm.columbia.edu/ and Java Climate Model at http://jcm.climatemodel.info/). 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 [SEP-5]** 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 GCM's. 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 IS 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*).

The rest of the IS in this course **investigate [SEP-3]** different Earth **systems [CCC-4]** and their interactions. By placing climate change early in the course, teachers can use climate impacts in California as a common thread that highlights the interdependence of Earth's systems (ESS2.A). This document describes specific climate impacts in each of the subsequent IS.

EEI Curriculum units, The Life and Times of Carbon and The Greenhouse Effect on Natural Systems (http://californiaeei.org/curriculum/), 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 IS to provide materials that examine CA EP&Cs III and IV.

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

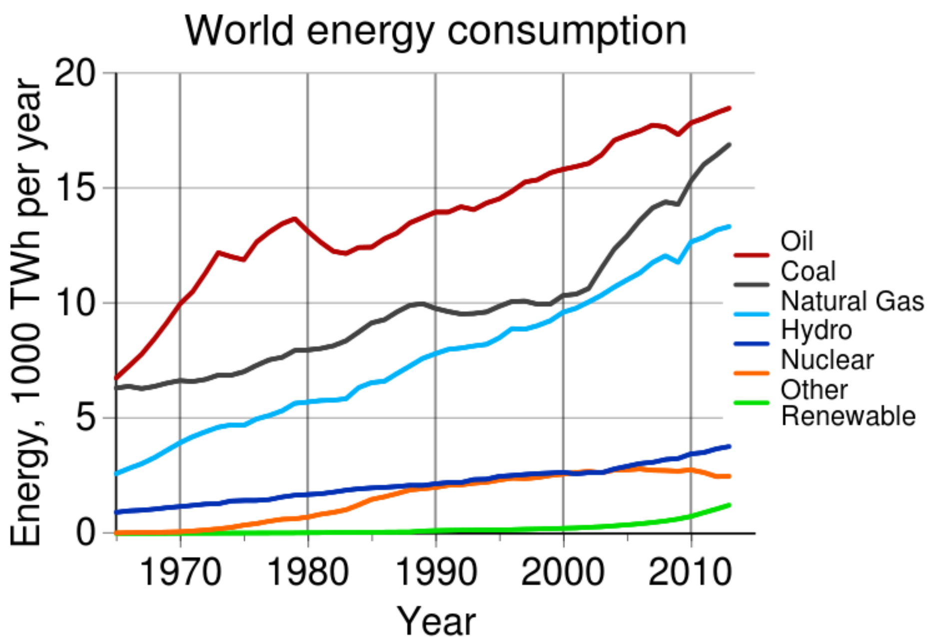


One example of how humans affect the climate, which impacts all parts of Earth's systems. Illustration by Dr. Art Sussman and Lisa Rosenthal, courtesy respectively of WestEd and WGBH.

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; CA 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 currently being researched. 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 US. 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; CA 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 2015.

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-6]** 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 (CA 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: 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 Chatelier'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 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: 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-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**	**PS1.B: Chemical reactions** **ESS2.A: Earth Materials and Systems** **ESS3.C: Human Impacts on Earth Systems** **ESS3.D: Global Climate Change** **LS2.A: Interdependent**	**[CCC-2] Cause and Effect** **[CCC-4] System and System Models** **[CCC-5] Energy and Matter: Flows, Cycles, and Conservation** **[CCC-6] Structure and Function** **[CCC-7] Stability and**

Thinking	Relationships in Ecosystems	Change
[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**	**LS2.B: Cycles of Matter and Energy Transfer in Ecosystems** **ETS1.C: Optimizing the Design Solution**	

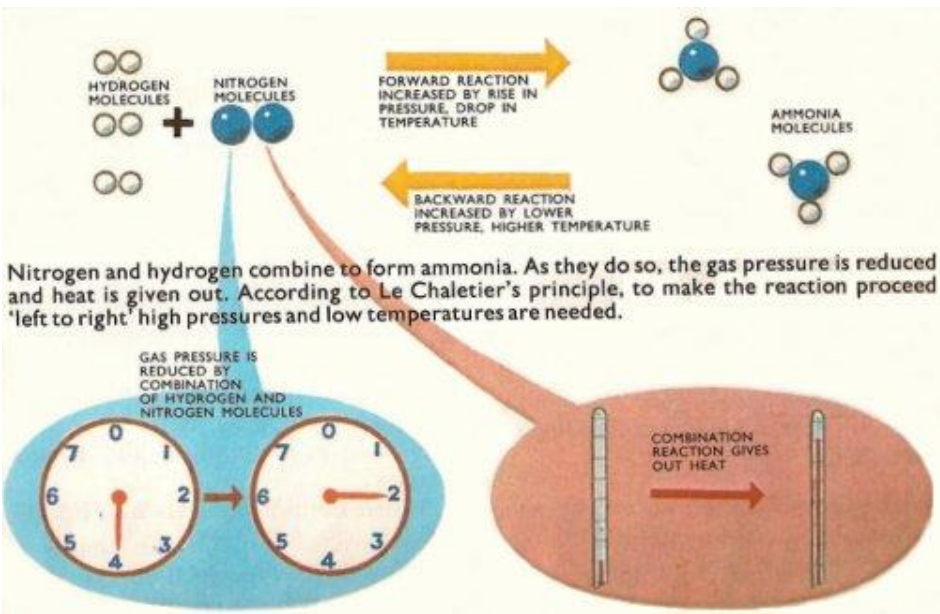
Highlighted California Environmental Principles & Concepts: Principle III Natural systems proceed through cycles that humans depend upon, benefit from and can alter. Principle IV The exchange of matter between natural systems and human societies affects the long term functioning of both.
CA CCSS Math Connections: N-Q.1-3; MP.2; MP.4
CA ELD Connections: ELD.PI.11-12.1,5,6a-b,9,10,11a
CA CCSS ELA/Literacy Connections: SL.11-12.5; RST.11-12.1,2

Stability [CCC-6] 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 must 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) → 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 Châtlier'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 Châtlier'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 Châtlier's Principle



Students should be able to apply Le Chatlier's principle to predict ways to increase the product of a chemical reaction. Source: The Worlds of David Darling 2015.

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 [$NaCl(s) \leftrightarrow Na^{+}(aq) + Cl^{-}(aq)$] 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).

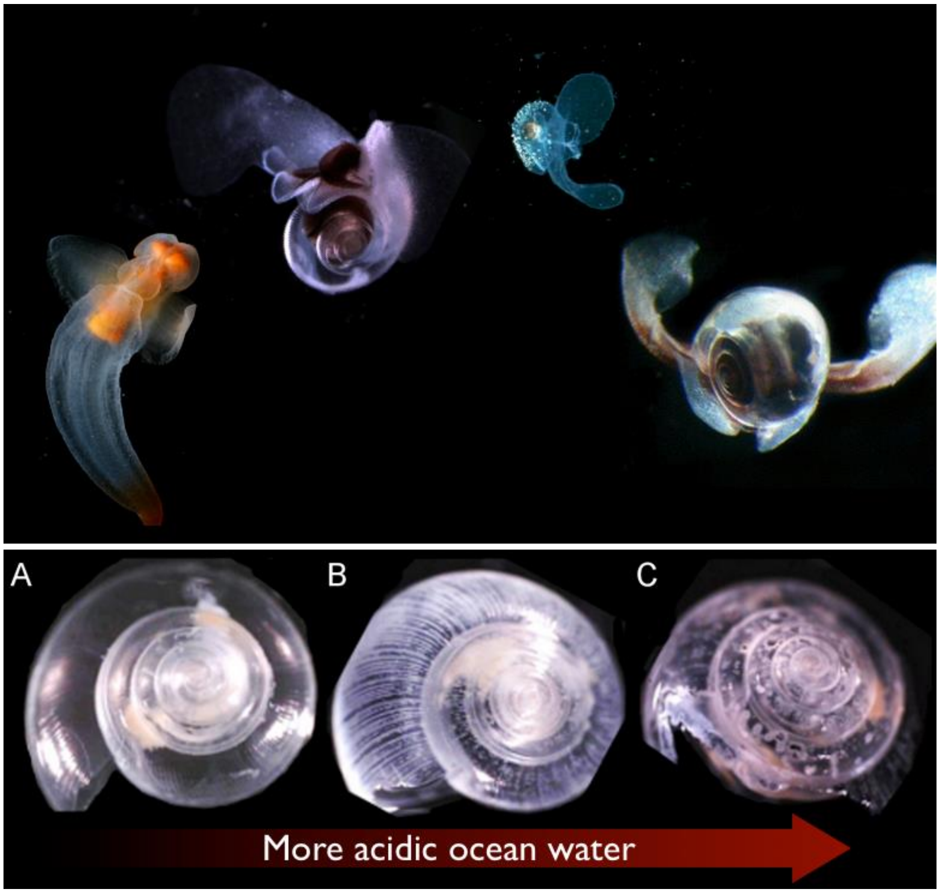
Disrupting Equilibrium in the Ocean

Changes [CCC-7] in the world's oceans bring together all science and engineering disciplines and are an excellent way to introduce principles of chemical dynamics. There are some excellent CA NGSS aligned resources for teaching about ocean chemistry, including well-designed curriculum sequences about ocean acidification (Institute for Systems Biology, Ocean Acidification: A Systems Approach to a Global Problem at http://baliga.systemsbiology.net/drupal/education/?q=content/ocean-acidification-systems-approach-global-problem). A good activity sequence begins by **obtaining and evaluating information [SEP-8]** in order to **define the problem [SEP-1]** *(HS-ETS1-1)*. In IS 5, 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 Life Science 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 (*CA 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 towards 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 that forms when CO_2 dissolves in seawater. While students may be familiar with some of the larger examples of these organisms like clam shells 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



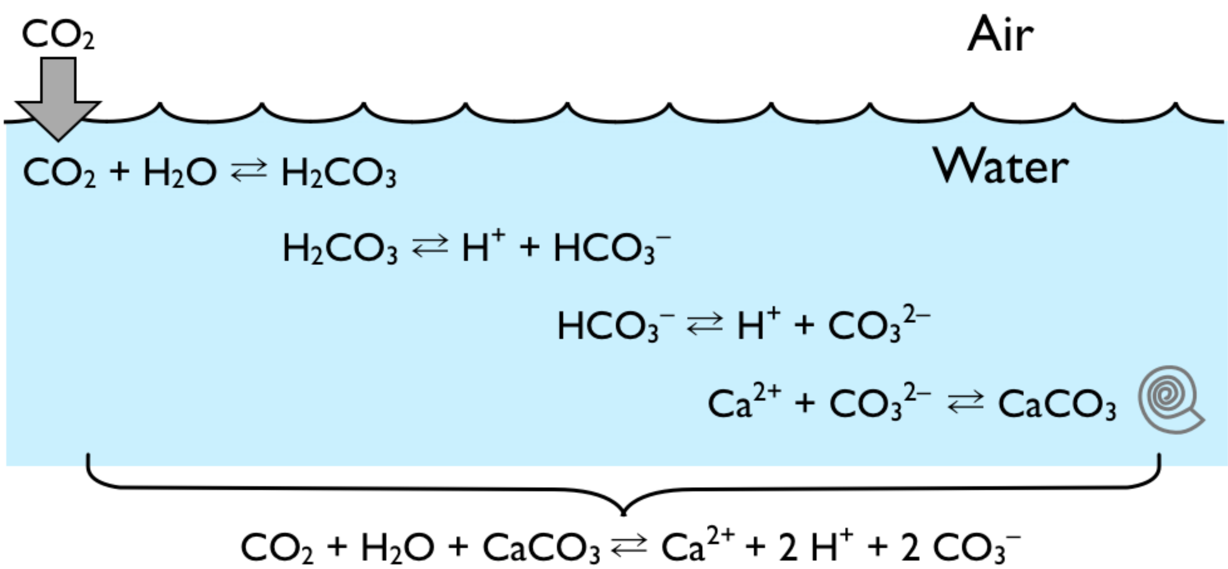
Pteropods are a delicate species of sea creature. The bottom panel shows laboratory experiments demonstrating how their shells dissolve when ocean water is too acidic. Sources: Hidden Ocean 2005 Expedition: NOAA Office of Ocean Exploration 2005; Hopcroft 2002; Auster and DeGoursey 2000; Hunt et al. 2010; Busch et al. 2014.

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 Chatelier'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 **obtain information [SEP-8]** on the health of coral reefs and coral bleaching, due in part to these pH changes.

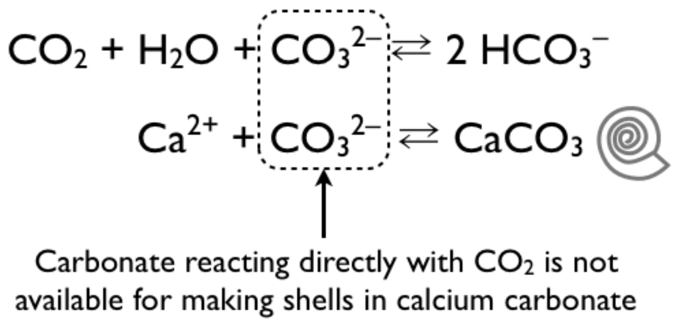
Figure 7.40. Chemical Interactions Between CO_2 and Water



A chain of chemical reactions occur 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.

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 them 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 PE 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 7.41, the same chemical **system [CCC-4]** can also be represented by figure 7.42.

Figure 7.41. Simplified Equations for Carbonate Shell Chemical Reactions



Source: M. d'Alessio

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.) 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).

High School Living Earth Vignette 7.2: Ocean Acidification, A Systems-based Approach to a Global Problem	
Performance Expectations	
Students who demonstrate understanding can:	
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-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-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-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.

Highlighted Science and Engineering Practices	Highlighted Disciplinary Core Ideas	Highlighted Crosscutting Concepts
[SEP-1] Asking Questions and Defining Problems	**PS1.B Chemical Reactions**	**[CCC-2] Cause and Effect**
[SEP-2] Developing and	**ESS3.C: Human Impacts**	**[CCC-4] System and System Models**

Using Models **[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**	**on Earth Systems** **LS2.A Interdependent Relationships in Ecosystems** **ETS1.C: Optimizing the Design Solution**	**[CCC-5] Energy and Matter: Flows, Cycles, and Conservation** **[CCC-7] Stability and Change**
Highlighted California Environmental Principles & Concepts: Principle I The continuation and health of individual human lives and of human communities and societies depend on the health of the natural systems that provide essential goods and ecosystem services. Principle II The long-term functioning and health of terrestrial, freshwater, coastal and		

marine ecosystems are influenced by their relationships with human societies. Principle III. Natural systems proceed through cycles that humans depend upon, benefit from and can alter. Principle V Decisions affecting resources and natural systems are complex and involve many factors.
CA CCSS Math Connections: MP.4; N-Q.1; F-LB.1b,c; S-ID.6,7
CA CCSS 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 IS of instruction for a discussion of chemical equilibrium.

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, Lesson 1: Cell phone network introduction at http://baliga.systemsbiology.net/drupal/education/?q=content/lesson-1-cell-phone-network-introduction).

5E Lesson Design – This sequence is based on an iterative 5E model. See the instructional strategies chapter for tips on implementing 5E lessons.

Day 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 6-9: Planning & 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. 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 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 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 webpage. 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 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 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 (CA *EP&Cs II, III, & IV*).

Day 5 – Ocean Acidification Specifics

Investigative phenomenon: Fish are 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.

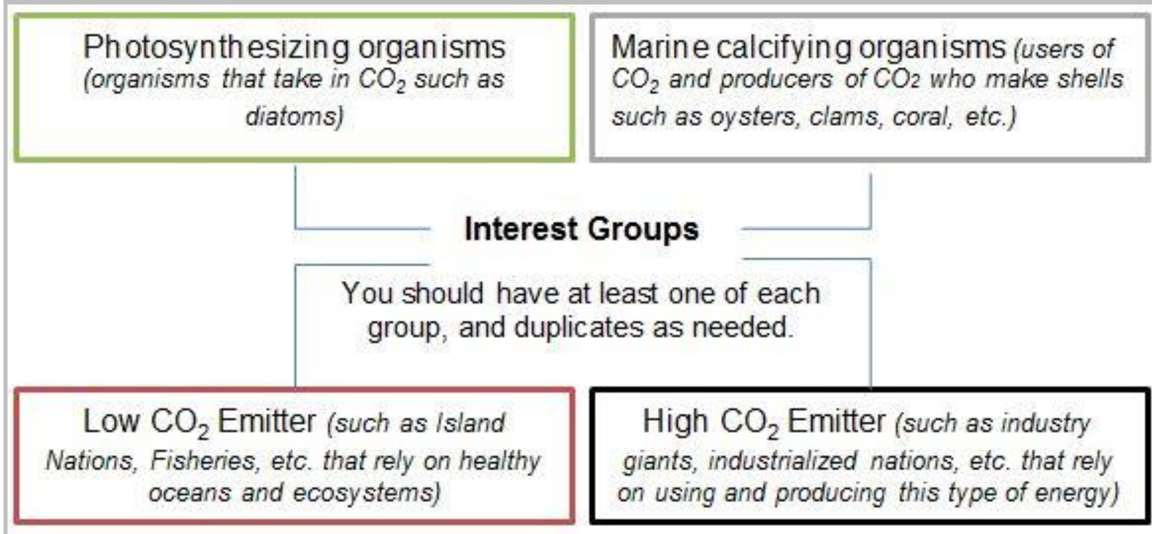
Day 6-9 – Planning & Conducting Investigations

Investigative problem: 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, 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



(Baliga Lab at Institute for Systems Biology 2013)

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

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 http://baliga.systemsbiology.net/drupal/education/sites/baliga.systemsbiology.net.drupal.education/files/L5_OA_TeacherResource-materials.docx) 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 would likely 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. The Low CO_2 emitters group is most concerned with the impact of acidification on their food supply, 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 bad ocean acidification 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 http://baliga.systemsbiology.net/drupal/education/?q=content/lesson-5a-ocean-acidification-experimentation) 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.

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, CA EP&Cs II, III*) (see Institute for Systems Biology, Ocean Acidification: A Systems Approach to a Global Problem – Lesson 5b at http://baliga.systemsbiology.net/drupal/education/?q=content/lesson-5b-online-data-and-supplemental-evidence). 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 (*CA 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 12 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.

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 the Baliga Lab at Institute for Systems Biology 2010. Please refer to them for much greater detail: http://baliga.systemsbiology.net/drupal/education/?q=content/ocean-acidification-systems-approach-global-problem (accessed August 5, 2016). They provide a recorded webinar walking through the lesson sequence and a number of downloadable resources.