# IS6 Chemistry in the Earth System Instructional Segment 6: The Dynamics of Chemical Reactions and Ocean Acidification

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

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

**Guiding Questions**

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

**Performance Expectations**

Students who demonstrate understanding can do the following:

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

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

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

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

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

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

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

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

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

| Highlighted Science and Engineering Practices | Highlighted Disciplinary Core Ideas | Highlighted Crosscutting Concepts |
|---|---|---|
| [SEP-2] Developing and Using Models<br>[SEP-4] Analyzing and Interpreting Data<br>[SEP-5] Using Mathematics and Computational Thinking<br>[SEP-6] Constructing Explanations (for science) and Designing Solutions (for engineering)<br>[SEP-7] Engaging in Argument from Evidence | PS1.B: Chemical Reactions<br>ESS2.A: Earth Materials and Systems<br>ESS2.D: Weather and Climate<br>ETS1.C: Optimizing the Design Solution | [CCC-1] Patterns<br>[CCC-5] Energy and Matter: Flows, Cycles, and Conservation<br>[CCC-7] Stability and Change |

**Highlighted California Environmental Principles and Concepts:**
**Principle III** Natural systems proceed through cycles that humans depend upon, benefit from and can alter.

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

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

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

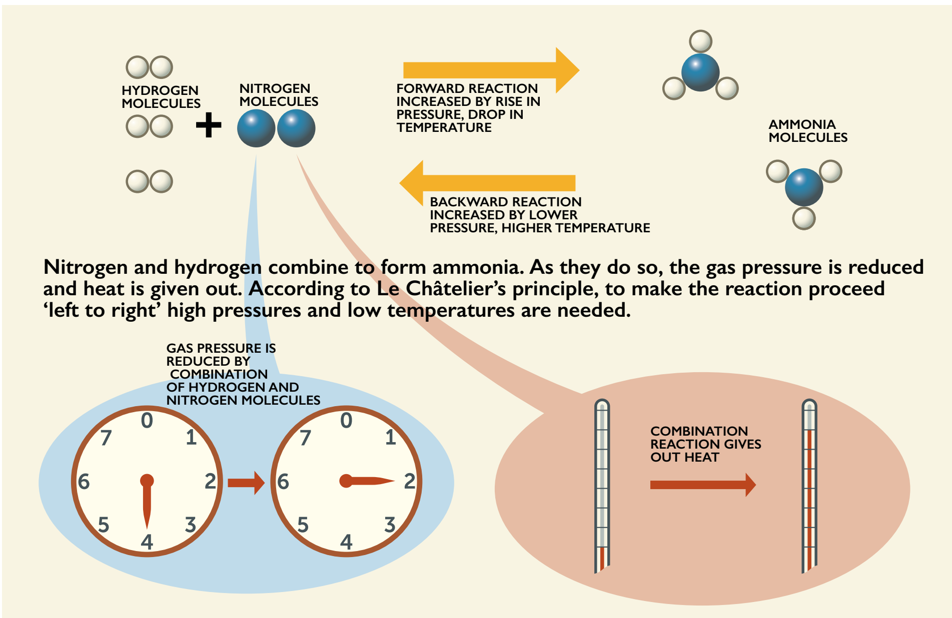
**CA ELD Connections:** ELD.PI.11–12.1, 5, 6a–b, 9, 10, 11a

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

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

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

**Figure 7.38. Le Châtelier's Principle**




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

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

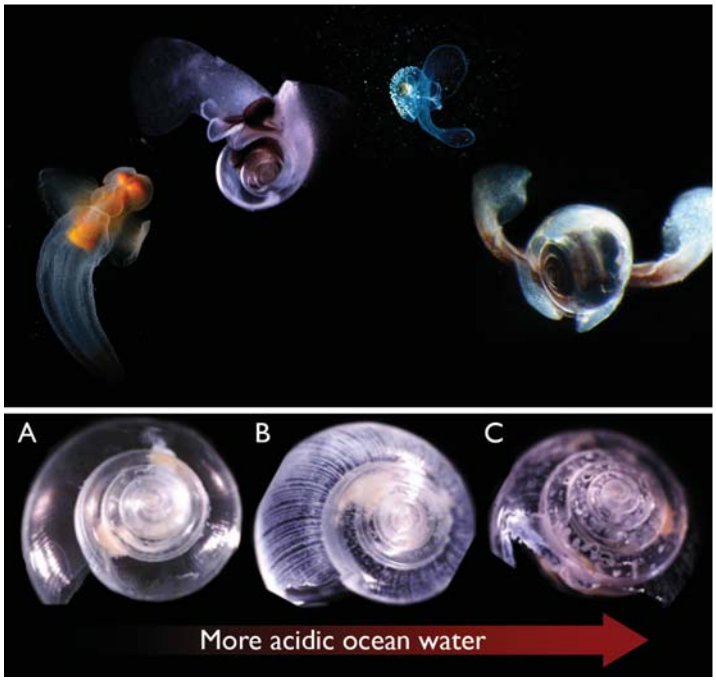
### *Disrupting Equilibrium in the Ocean*

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

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

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

**Figure 7.39. Pteropods**



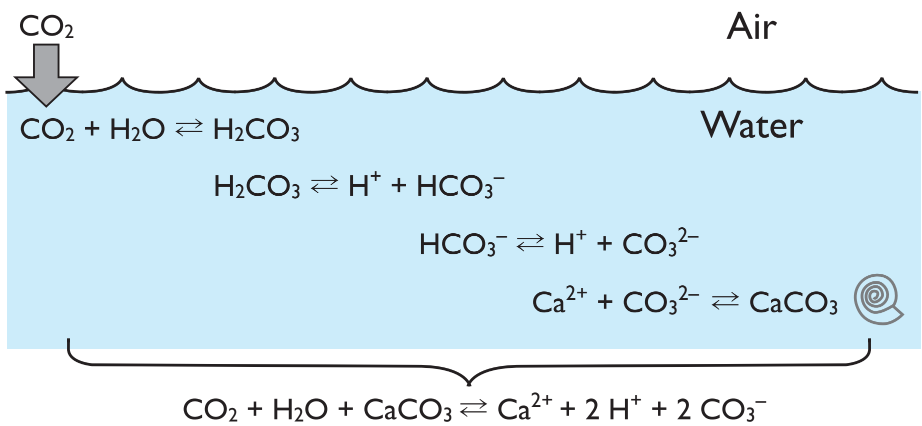

Pteropods are a delicate type of sea creature. The bottom panel shows laboratory experiments demonstrating how their shells dissolve when ocean water is too acidic. *Sources*: National Oceanic and Atmospheric Administration/Department of Commerce, Kevin Raskoff, Hidden Ocean 2005 Expedition: NOAA Office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

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

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

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

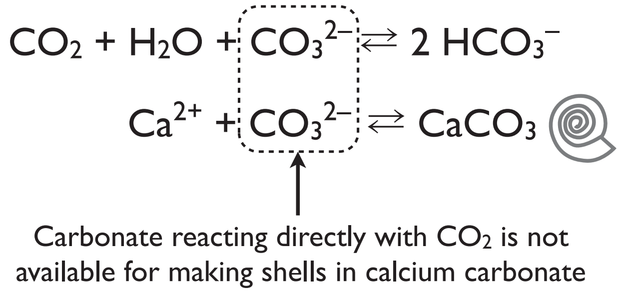
**Figure 7.40. Chemical Interactions Between $CO_2$ and Water**




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

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

**Figure 7.41. Simplified Equations for Carbonate Shell Chemical Reactions**




*Source*: M. d'Alessio

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

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

**Performance Expectations**

Students who demonstrate understanding can do the following:

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

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

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

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

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

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

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

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

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

**Highlighted California Environmental Principles and Concepts:**

**Principle I** The continuation and health of individual human lives and of human communities and societies depend on the health of the natural systems that provide essential goods and ecosystem services.

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

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

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

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

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

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

### Introduction

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

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

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

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

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

**Days 1–2: Interconnected Systems**

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

**Days 3–4: Exploring $CO_2$**

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

**Day 5: Ocean Acidification Specifics**

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

**Day 6: Planning and Conducting Investigations**

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

**Days 7–9: Online Simulations**

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

**Day 10: Summit**

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

### Days 1–2: Interconnected systems

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

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

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

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

### Days 3–4: Exploring $CO_2$

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

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

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

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

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

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

### Day 5: Ocean Acidification Specifics

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

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

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

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

### Days 6–9: Planning & Conducting Investigations

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

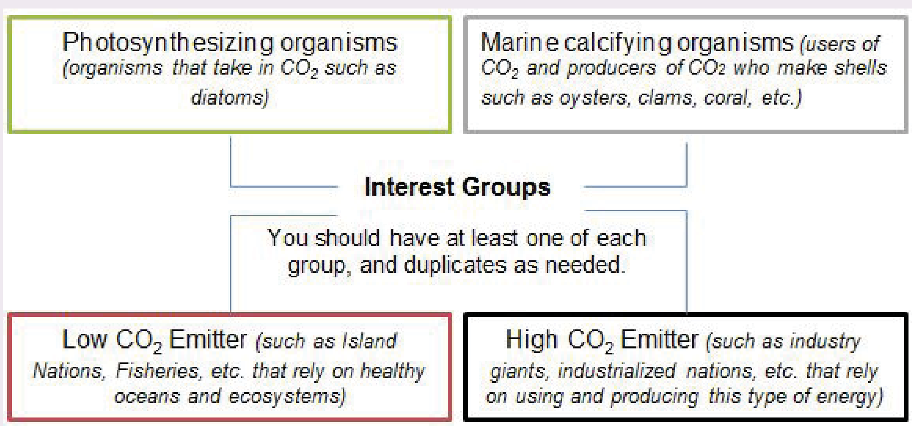
Ocean acidification involves a huge range of organisms and people. Ms. K tells students that the class will divide up into different interest groups to investigate specific causes,

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

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

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

**Figure 7.42: Four Interest Groups**




*Source*: Baliga Lab at Institute for Systems Biology 2013

**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

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

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

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

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

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

**Day 10: Online research and computer simulations**

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

**Day 11: Summit**

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

## Vignette Debrief

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

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

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

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

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

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

**Resources:**

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