Appendix 3
Computer Science in Science

2016 Science Framework

FOR CALIFORNIA PUBLIC SCHOOLS
Kindergarten Through Grade Twelve

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

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

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

Integrating the Practices of Computational Thinking, Computer Modeling, and Simulation to Teach the California Next Generation Science Standards

By Irene Lee, Director, Project GUTS, Research Scientist, MIT Scheller Teacher Education Program/Education Arcade

Computer science plays a central role in modern scientific research and practice and in generating economic opportunity in California. Thus, all California students should be better prepared to incorporate computational concepts and methods as an integral part of their science education. The inclusion of modern scientific practices of computational thinking, computer modeling, and simulation are included in the *CA Science Framework* to support application of computer science in secondary classrooms. In this appendix, a variety of examples are offered for forging a deeper connection between computer science and science and engineering through computer modeling and simulation. Incorporating these practices has been found to be highly engaging to a wide variety of students while supporting instruction of specific CA NGSS middle grades and high school standards.

A computer model is a computer-based representation of the system that includes specification of objects or components and their state variables, as well as programmed relationships among variables or components, based on known scientific theory. When a computer model is used to mimic the system moving forward in time, it is called computer "simulation." Computer simulations may be augmented by graphs of relationships between variables over time or, put another way, how output variables evolve over time for given input conditions.

Simulations designed for teaching usually include visualizations designed to present students with a representation of otherwise invisible processes. It is of utmost importance that students inspect and analyze the computer code that underlies computer models; therefore we refrain from presenting simulations as black boxes that cannot be investigated.

The computer models presented in the vignettes that follow are agent-based models, a particular type of computer model in which artificial worlds are created out of agents, their environment, and interaction between agents and their environment. This type of modeling is particularly suitable for middle and high school students because the behaviors of individual agents can be described in computer code without the use of higher-level mathematics. Instead, students describe the behavior of agents from a first-person perspective as actions and reactions. Then, when the passage of time is simulated, emergent patterns appear as a product of the actions and interactions of agents. Agent-based models have been used by researchers, ranging from young students to research scientists, as a tool to study the behavior of complex systems.

Computational thinking is a key thinking skill used when one is engaged in creating and modifying computer models. Computational thinking is the human thought process used when deciding what aspects of the real world are important to represent in a computer model. Computational thinking also is used when developing algorithms to simulate agent behaviors and analyzing if a computer model is a valid representation of the real world (for the purposes of answering the particular question at hand). Computational thinking can be developed progressively across the grades as students develop algorithms and describe the components necessary to include in their computer models. Understanding that someone has abstracted the real world into a model and has developed instructions to tell the components of the model how to behave is fundamental to understanding what comprises models, what models are good for, and what limitations models may possess.

Concrete steps can be taken to support the development of computational thinking in middle and high school students. The first is to read and decode computer models. For example, in the StarLogo Nova environment, the student can “look under the hood” and inspect the causal relationships and abstractions that are embedded in a model. Second, a three-stage progression called Use-Modify-Create can support and deepen youth’s interaction with computer models. In the Use stage, students are consumers of someone else’s creation. For example, they decode and run experiments using pre-existing computer models. Over time they begin to Modify the model with increasing levels of sophistication. For example, a student may initially want to change the color of a character or some other purely visual attribute. Later the student may want to change the character’s behavior in a way that entails developing new algorithms in code. Through a series of modifications and iterative refinements, new skills and understandings are developed as what was once someone else’s model becomes one’s own. Finally, students reach the Create stage in which they make a model of their own, either through multiple modifications or starting from a blank slate.

Importantly, modeling and simulation have been shown to have broad appeal and to provide students from diverse backgrounds and a range of educational needs with opportunities to successfully engage in modern scientific practice. Project GUTS (Growing Up Thinking Scientifically) and NM-CS for All (New Mexico Computer Science for All) serve student populations that are more than 70 percent from underrepresented groups in science, technology, engineering, and mathematics (STEM), including Native Americans, African Americans, Hispanics/Latinos, and young women. In these programs, students have been able to incorporate their own reality into scientific investigations through computer modeling and simulation resulting in deep engagement in CA NGSS content and practices.

Appropriate Use of Technology—Bifocal Modeling Framework

Computer modeling is a crucial aspect of the CA NGSS, but how does it fit into the broader curriculum? What is the balance between computational investigations and real-world investigations? This section describes one example of an appropriate marriage between these different types of scientific experiences that maximizes the value of each.

In their daily work, scientists and engineers not only make use of computers to analyze data, communicate, calculate, and model systems, they also employ highly technical equipment, including specialized probes and instruments, to extend their ability to experiment with and make observations of phenomena.

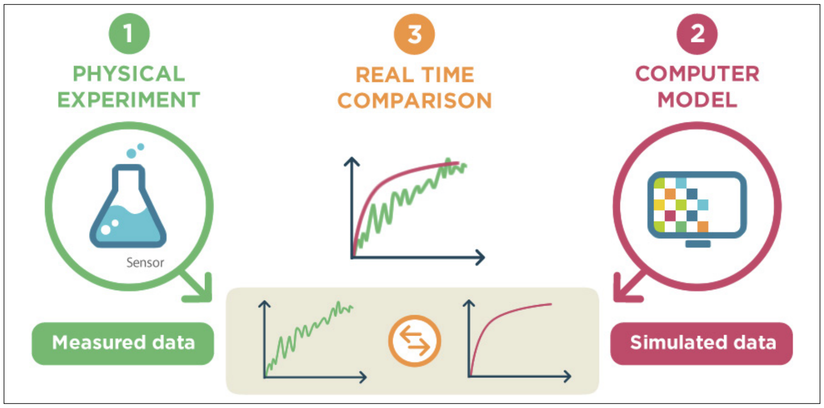
The CA NGSS science instruction should include resources for students to engage with and even design technology-based tools to

- plan and perform investigations;
- explore and make predictions from provided computer simulations;
- create new or extend existing computer simulations;
- understand how these simulations incorporate science theory in their underlying computational models;
- analyze and display data;
- search for information;
- communicate findings;
- collaborate.

The use of graphing calculators and computer-linked measurement tools greatly expand students' ability to measure, record, and analyze a sufficient quantity of data to reach meaningful conclusions. Creating new, or extending existing computer models, and understanding how simulations incorporate science theory in their underlying computational models are additional ways that technology is an essential tool for the full implementation of the CA NGSS. Specifically, students engaged in computer modeling and simulation use the engineering design cycle as they iteratively develop and refine their models and exemplify how technology is an essential tool in modern scientific investigation. As students develop a deeper understanding of and ability to reason with data, the level of complexity in technology use and of students' capacity for computational thinking progresses with each grade level. The need for creating more sophisticated analysis tools, including coding capability, increases as students engage in understanding phenomena that are characterized by large data sets or complex relationships between multiple variables. Because computer models are written in code, the creation, modification, and inspection of computer models can be achieved if students are provided with age-appropriate computer science instruction that enables them to read and edit the code. Organizations and programs such as Code.org (https://www.cde.ca.gov/ci/sc/cf/appx3.asp#link1), Santa Fe Institute's Project GUTS (https://www.cde.ca.gov/ci/sc/cf/appx3.asp#link2), and Northwestern University and NetLogo (https://www.cde.ca.gov/ci/sc/cf/appx3.asp#link3) provide valuable free resources that create opportunities for students to develop new or use existing computational models and simulations of systems in the context of life, physical, and Earth sciences aligned to the CA NGSS.

It is important to note, however, that computer simulations should be used to aid and extend students' understandings of scientific concepts and should not completely replace the hands-on experience of interacting with a real experiment and making sense of real data. The Bifocal Modeling (https://www.cde.ca.gov/ci/sc/cf/appx3.asp#link4) project from Stanford University is an example of how to develop experiences for students through the parallel use of real experiments and computational models of the same experiment (see figure app 3.1). These activities allow students to learn scientific content while deepening their modeling skills, facility with scientific instrumentation, computational thinking, and understanding of how science builds knowledge and engineering solves problems (Fuhrmann et al. 2012; Salehi et al. 2013). Whenever possible, teachers should emphasize the existing discrepancies between a simulation and a real experiment to emphasize the limitations, accuracy, and credibility of both simulation and experiment.

Figure App 3.1: Representation of the Bifocal Modeling Framework from Stanford University



Source: Transformative Learning Technologies Lab 2013
Long description of Figure App 3.1.

Effective science instruction in K–12 uses technology to teach and engage students, assess students' demonstration of knowledge in multiple formats and media, increase their technological and scientific literacy, and engage students as young computational scientists. Even in elementary grades, there are many valuable teaching tools and resources accessible through computers, tablets, or even cell phones. Choosing how and when to use such tools and resources are important elements of instructional planning. Too often students experience technology as end-users or consumers of products made by others. In science, students should not be trained to blindly accept the models and theories put forth by others as black boxes, but instead should use technology to its fullest potential as a tool.

Curriculum developers also need to attend to the technological and computational elements. They should ensure that curriculum incorporates high-quality resources that engage students as creators of models who can run simulations and, as needed, use appropriate computer-linked measurement probes. Curriculum should also provide links to quality open-source materials and pedagogical supports for teachers to effectively incorporate these technological tools and resources throughout their instruction.

Finally, all science educators should leverage the increased use of technology included in the CA CCSSM and the CA CCSS for ELA/Literacy. For example, searches for information through the Internet, evaluation of the reliability of informational resources, and interpretation of data available through external databases are all important components of obtaining, evaluating, and communicating information. These technology-related skills are equally important in the context of CA CCSSM and the CA CCSS for ELA/Literacy as they are for the CA NGSS. All teachers, not only science teachers, should take advantage of skills that students develop across multiple disciplines and should support the ongoing development of these skills. This includes the development and use of computational and technology-based tools in multiple contexts and learning environments.

Description of the Vignettes

The vignettes presented below are examples of how teaching and learning may look in the classroom when the CA NGSS are implemented. The purpose of the vignettes is to illustrate how a teacher engages students in three-dimensional learning by providing students with the opportunity to engage in the **science and engineering practice (SEPs)** of computational thinking and the **crosscutting concepts (CCCs)** of systems and system models to understand **disciplinary core ideas (DCIs)**. It is important to note that the vignettes focus on a limited number of performance expectations. They should not be viewed as showing all instruction necessary to prepare students to fully achieve these performance expectations. Neither do they indicate that the performance expectations should be taught one at a time.

The vignettes assume that the students have completed a multi-day introductory sequence in computer modeling and simulation (e.g., Module 1 of the Code.org Computer Science in Science curriculum at https://www.cde.ca.gov/ci/sc/cf/appx3.asp#link5) so that they have the skills required to perform the expected modeling. Students will need basic skills in reading and modifying computer codes. They will need to interpret an existing base model and make modifications to it by adding new codes or altering the ones that exist.

Structure of the Vignettes

The vignettes that follow describe a series of instructional modules and the CA NGSS performance expectations (PEs) they meet. Each module follows a common trajectory across five 50-minute lessons and uses the 5E learning approach. In the first lesson, students participate in an experience that grounds their knowledge and/or stimulates prior knowledge on the topic (Engage). In the second lesson, students inspect the base model to learn about the elements in the model and how the behaviors and interactions of those elements are implemented. Then the students design and run an experiment of their choice (Explore). In the third lesson, students first modify the base model to add a variable and then experiment with changing a variable and analyzing the impact the change has on the system (Explain). In the fourth lesson, students brainstorm how to customize the model to answer new questions. Then students design new experiments, and implement the customized model (Extend). Finally, in the fifth lesson, students test their models, run controlled experiments with the new model as a testbed, collect and analyze data, and share findings with classmates (Evaluate). Two optional days are included so that students can further develop models to investigate human impacts on the system and design, implement, and test mitigation strategies. The 5E learning approach parallels the science and engineering practices (SEPs) of CA NGSS in many ways but applies them from the perspective of lesson design. While SEPs should be shared explicitly with students, the 5Es are only for the benefit of the teacher.

Day 1: Introduction to the module (Engage) Students participated in an experience that grounded their knowledge and/or stimulated prior knowledge on the topic.	**Day 2: Decoding and using the base model to run experiments (Explore)** Students inspected the base model to learn about the implementation of behaviors and interactions. Then the students designed and ran an experiment of their choice.	**Day 3: Modifying the base model and investigating the impact of changing variables (Explain)** Students experimented with changing a variable and witnessing the impact the change had on the system.
Day 4: Extending the model and running an experiment (Extend) Students added a feature to the modeled system and designed an experiment to investigate the impact of the addition on the system. Then they used their model to run controlled experiments and tracked the outcomes of subsequent runs of the model.	**Day 5: Testing and evaluation of the model (Evaluate)** Students tested their models and considered whether their models were working and reflected the real-world phenomenon.	**Days 6–7 (optional): Computational science & engineering challenge** Students designed and implemented models to investigate human impacts on the system and/or test strategies that might mitigate system disruption caused by humans.

Note that each of the three modules described below engaged students in the eight science and engineering practices outlined in the National Research Council's *A Framework for K–12 Science Education* (2012) and fulfill specific CA NGSS performance expectations. Additionally, computer modeling and simulation present a concrete way to make explicit the links between science and engineering. Computer models are engineered designs expressed in computer code. Students engage in computer modeling and simulation using the engineering design cycle as they iteratively design, implement, and refine their models.

Middle Grades Earth and Space Science Vignette: Greenhouse Gases

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Performance Expectations

Students who demonstrate understanding can do the following:

MS-ESS3-3. Apply scientific principles to design a method for monitoring and minimizing a human impact on the environment.* [Clarification Statement: Examples of the design process include examining human environmental impacts, assessing the kinds of solutions that are feasible, and designing and evaluating solutions that could reduce that impact. Examples of human impacts can include water usage (such as the withdrawal of water from streams and aquifers or the construction of dams and levees), land usage (such as urban development, agriculture, or the removal of wetlands), and pollution (such as of the air, water, or land).]

MS-ESS3-4. Construct an argument supported by evidence for how increases in human population and per-capita consumption of natural resources impact Earth's systems. [Clarification Statement: Examples of evidence include grade-appropriate databases on human populations and the rates of consumption of food and natural resources (such as freshwater, mineral, and energy). Examples of impacts can include changes to the appearance, composition, and structure of Earth's systems as well as the rates at which they change. The consequences of increases in human populations and consumption of natural resources are described by science, but science does not make the decisions for the actions society takes.]

MS-ESS3–5. Ask questions to clarify evidence of the factors that have caused the rise in global temperatures over the past century. [Clarification Statement: Examples of factors include human activities (such as fossil fuel combustion, cement production, and agricultural activity) and natural processes (such as changes in incoming solar radiation or volcanic activity). Examples of evidence can include tables, graphs, and maps of global and regional temperatures, atmospheric levels of gases such as carbon dioxide and methane, and the rates of human activities. Emphasis is on the major role that human activities play in causing the rise in global temperatures.]

MS-ETS1-1. Define the criteria and constraints of a design problem with sufficient precision to ensure a successful solution, taking into account relevant scientific principles and potential impacts on people and the natural environment that may limit possible solutions.

MS-ETS1-2. Evaluate competing design solutions using a systematic process to determine how well they meet the criteria and constraints of the problem.

MS-ETS1-3. Analyze data from tests to determine similarities and differences among several design solutions to identify the best characteristics of each that can be combined into a new solution to better meet the criteria for success.

MS-ETS1-4. Develop a model to generate data for iterative testing and modification of a proposed object, tool, or process such that an optimal design can be achieved.

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

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Highlighted Science and Engineering Practices	Highlighted Disciplinary Core Ideas	Highlighted Crosscutting Concepts
[SEP-1] Asking questions and defining problems [SEP-2] Developing and using models [SEP-4] Analyzing and interpreting data [SEP-6] Constructing explanations and designing solutions [SEP-7] Engaging in argument from evidence	ESS3.C: Human Impacts on Earth Systems ESS3.D: Global Climate Change ETS1.A: Defining and Delimiting Engineering Problems ETS1.B: Developing Possible Solutions ETS1.C: Optimizing the Design Solution	[CCC-2] Cause and Effect: Mechanism and Explanation [CCC-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: 7.RP.2c–d; MP 1, 3, 6

CA CCSS for ELA/Literacy Connections: SL.6–8.1a–d, 4, 5; RST.6–8.3, 9; WHST.6–8.1

CA ELD Connections: ELD.PI.6–8.1, 5, 6a–b, 9, 10, 11a

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Introduction

Motivated by computing their own carbon footprint and learning about greenhouse effect, students apply and refine their existing model about Earth's energy balance. As budding computational-enabled scientists, students articulate the mechanisms by which human activities alter the local climate system and ultimately design mitigation strategies to reduce that impact.

The goal of this vignette is to clarify what is known about climate change, what scientists believe is happening, and how changes in climate impact our environment and species by acting as computational scientists. The students learn to use, modify, and customize a computer model of the build-up of greenhouse gases and its impact on the climate. As in many scientific endeavors, the students are challenged to be precise with their scientific language, to be explicit in describing their conceptual models, and to revise their models as new evidence is produced. As computational scientists, students learn to represent conceptual models by decoding, using, modifying, and creating computer models. As students gain experience with computational thinking, modeling and simulation, and data analysis—scientific practices key to the CA NGSS—they gain a better understanding of the DCIs and CCCs.

Length and position in course: This vignette describes one week of instruction based on Project GUTS' Computer Science (CS) in Science module on greenhouse gases. This module describes how computer models can be developed, used, and analyzed in the context of studying Earth-atmosphere systems. Activities related to the urban heat islands (HS) and the albedo effect will naturally follow from this vignette because this module sets the stage for understanding feedback loops in complex systems.

This vignette could support and extend students' existing **models [SEP-2]** of Earth's energy balance or provide students initial exposure to the factors that affect a system's temperature (that could later be extended to the global **scale [CCC-3]** of Earth's climate).

Prior knowledge. This vignette assumes that students have completed a multi-day sequence introducing computer modeling and simulation (such as module 1 of the Code.org *Computer Science in Science* curriculum). Students need basic skills in reading and modifying computer codes. They need to interpret an existing base model and make modifications to it by adding new codes or altering the ones that exist. While this vignette provides opportunities to practice those skills, they are not specifically addressed in this lesson outline.

Teacher background—The Greenhouse Effect

The physics behind the greenhouse effect is well understood. Solar radiation passes through the clear atmosphere. Although some of the radiation is reflected by the Earth and the atmosphere, most is absorbed by Earth's surface. Some of the infrared radiation passes through the atmosphere and some of it is absorbed and re-emitted in all directions by greenhouse gas molecules. The energy that is absorbed warms the Earth's surface and the lower atmosphere.

Certain naturally occurring gases, such as carbon dioxide (CO_2) and water vapor (H_2O), trap heat in the atmosphere causing a greenhouse effect. Burning fossil fuels—like oil, coal, and natural gas—adds CO_2 to the atmosphere. There is now more CO_2 in the atmosphere

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than at any time in the past 650,000 years. The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Intergovernmental Panel on Climate Change 2007) concluded that "most of the observed increase in the globally averaged temperature since the mid-twentieth century is very likely due to the observed increase in anthropogenic (of human origin) greenhouse gas concentrations."

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: Introduction to Climate Change and the Greenhouse Gases Base Model (Engage)

Students calculate their personal carbon footprint and begin to consider how their everyday actions contribute to greenhouse gas emissions. Then they observe and interact with the computer model of greenhouse gases.

Day 2: Decoding and using the Greenhouse Gases Model to Run Experiments (Explore)

Students examine and decode the computer model then interpret what mechanisms were implemented. Then they run the model to illustrate a simple experiment.

Day 3: Modifying the Base Model and Investigating the Albedo Effect (Explain)

Students add an albedo slider and design an experiment to investigate the impact of changing the Earth's albedo. Then they use the model to run experiments by changing the variable albedo in subsequent runs of the model.

Day 4: Adding CO2 to the Model (Extend)

Students reflect on their carbon footprints and then extend the base model to incorporate human CO_2 production.

Day 5: Testing and Evaluation of the Model (Evaluate)

Students consider whether their models are working and reflect the real-world phenomenon of greenhouse gases.

Days 6–7 (optional): Computational Science and Engineering Challenge

Students design potential mitigation strategies and implement them in their model. They test the strategy within the model and examine its impact.

Day 1: Introduction to Climate Change and the Greenhouse Gases Base Model (Engage)

Ms. P. engaged students in a discussion of climate change and greenhouse gases stimulated by watching an Environmental Protection Agency (EPA) video called *The Greenhouse Effect* and completing an online activity. The short video served to provide discussion points and introduced key concepts related to climate change. In the online activity, students navigated to an online Carbon Footprint Calculator on the EPA Web site and used the calculator to gain an understanding of how their everyday actions contribute to greenhouse gas emissions. Next they considered ways of reducing their carbon footprint. Ms. P asked the

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students, “Who is saving more carbon and why?” and “What is the easiest change to make that will reduce carbon emissions and why?” inviting students to link their own experience with the topic of the unit.

Investigative phenomenon: Changing the amount of greenhouse gas in the atmosphere alters the temperature of the Earth.

Next, Ms. P. opened the StarLogo Nova base model of greenhouse gases and used the projector to demonstrate how it works to the class. Students were shown how to use the “setup” and “run forever” buttons to reset and run the model. Ms. P asked students to tell her what to do next and to interpret what they were seeing when the model was run. She asked, “What are the elements in this model?” and heard that the model contains a Sun, solar radiation, reflected solar radiation, and infrared radiation. Ms. P asked, “When the model was run or executed what happened?” and heard various interpretations of what was seen, including, you hit the “show graph” button and the temperature showed a big increase,” “The world continued to get hotter,” and “The temperature continued to jump around.” After running the model several times and **comparing [SEP-4]** the **pattern [CCC-1]** of temperature change generated by the model, students wrote a summary statement, “Temperature increased for a while then stayed around the same temperature.” Ms. P explicitly drew their attention to **stability and change [CCC-7]**, noting that it is common for systems to stabilize after experiencing a change. Ms. P also noted that each run of the computer model produced slightly different results, which led to a discussion of what computer models are good for and how they can help us understand climate impacts (ESS2.D).

Day 2: Analysis and Use of the Greenhouse Gas Model to Run Experiments (Explore)

In the first activity of this lesson the students reviewed familiar code blocks prior to inspecting the model’s code. Ms. P assigned partners to work together and then assigned each pair a segment of the model’s code to examine and decode. Students used a graphic organizer called a “model observation form” to document what each of the assigned procedures did to simulate the behavior of the Sun, Solar Energy, Heat, Reflected Energy, or The World. After five minutes of decoding, Ms. P asked the students to share their findings. Following each pair’s reporting about what mechanisms or behaviors were implemented in the algorithms, Ms. P asked if students had other interpretations of what the code does. Any dissension was resolved by **looking closely at the source for evidence [SEP-7]**—the code itself. Ms. P concluded the activity by discussing the main program loop and execution order. She had students draw a diagram mapping out the sequence of the different procedures and sub-procedures. She then had students enact their diagram as a physical model with pairs of students moving around the room from one procedure to the next to the next to simulate the execution of the code starting with the pressing of the setup button.

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Investigative phenomenon: Different surfaces reflect different amounts of energy, which alters the temperature of the Earth.

In the second activity of this lesson, students learned how to use the model to **run an experiment [SEP-3]** by changing the variable related to albedo. During their decoding, students noted the procedures that simulate the behavior of solar radiation as it reaches the Earth. Ms. P made sure that students could relate this computer code to the **flow of energy [CCC-5]** in the physical situation by asking, "What happens to the solar energy when it hits the ground?" Students responded that "Some of the time, the solar energy turns into reflected energy and heads out into space (the yellow dots). Other times it shows up as infrared radiation (red dots, "heat"). The temperature of the Earth is determined by how many "heat agents" there are floating around." In the base model the code was set so that "60 percent of the time, the radiation is simply reflected back to space, but 40 percent of the time "heat" is generated, causing the temperature to increase." Ms. P asked, "Do you think there are some surfaces that reflect more solar energy than others?" She pointed to how different colors of cars seem to get warmer faster. Students responded that perhaps this "albedo"—the reflectivity of surfaces—depends on the surface type. Ms. P drew the real-world connection to ice and snow that are much lighter in color than other Earth surfaces and reflect more solar energy. She then asked, "What do you think would happen if more solar energy were reflected instead of turning into heat?" Students wrote down their prediction. Next, students located this variable in the code, changed the variable to represent a different surface, and started the model again. She assigned some students to mimic a snowy surface with lighter colors while other students represented a darker colored surface such as ash after a forest fire.

Ms. P asked the students to **compare and analyze [SEP-4]** the results of their model runs and to determine whether their prediction was correct. Students found that an albedo higher than 60 **caused [CCC-2]** more solar radiation to reflect off the Earth's surface and the overall temperature was lower than the base case. An albedo lower than 60 caused more solar radiation to be absorbed and converted to infrared radiation, and the overall temperature was higher.

Day 3: Modification of the Base Model and Investigation of the Albedo Effect (Explain)

In the third activity, students added new computer code to create a slider on the user interface panel that adjusted the albedo variable, and then designed and ran more experiments using the slider to control the albedo. Students then posed **questions [SEP-1]** about the effect of albedo on the climate model and reflected on the real-world implications of their discoveries. The model allowed them to answer all sorts of "what-if" questions. A graphic organizer Ms. P called an "experimental design form" guided students to develop scientific questions that they could investigate using their model. Along with scaffolding, the form then

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helped the students see the need to use trials and to clearly identify the variables. Students designed and ran their experiment in pairs after specifying which variable they would change, within what range, and how many trials at each setting. They used the instrumentation in the model (the graph and the data boxes) to monitor temperature under the different scenarios; students recorded the data from the graph. Then they **analyzed [SEP-4]** the results of their experiments, documented the **patterns [CCC-1]** in their findings, and used these as evidence to support a claim **explaining [SEP-6]** one aspect of the system.

Ms. P used direct instruction to introduce feedback loops, an advanced form of **cause and effect mechanisms [CCC-2]**. She described a feedback loop as a closed system in which outputs become inputs to the system.

> There are two kinds of feedback: reinforcing (or positive) and balancing (or negative). Reinforcing feedbacks amplify or accelerate a change away from a starting point whereas balancing feedback dampens, slows down, or corrects a change in a system that is moving away from the starting point. There are many feedback loops in the global climate system. Some are not very well understood yet, and there are probably many feedback loops that we haven't even recognized yet. One well-known feedback loop describes the effect that melting ice caps and glaciers will have on climate change. As the temperature rises, ice will melt, and there will be fewer white, reflective surfaces on the planet, decreasing the planet's albedo and causing it to absorb more solar radiation, which will heat the planet up even more.

Finally, students were asked to think of ways to improve the model, based on what they have learned about climate change, greenhouse gases, and human contributions to the increase of CO_2. (Notably, the greenhouse gases were missing from this greenhouse gas model!)

Day 4: Addition of CO_2 to the Model (Extend)

> **Investigative phenomenon:** Changing the amount of greenhouse gas in the atmosphere alters the temperature of the Earth. *(Revisited in more detail from day 1.)*

Ms. P started off the day by asking, "Do humans produce greenhouse gases?" referring back to the activity from day 1, the carbon footprint activity (ESS 3.D). She then proceeded to ask students how CO_2 could be added to the base model. Students suggested adding to the model a factory that emits CO_2 into the atmosphere. Students were then tasked with modifying the Greenhouse Gas base model by adding a factory that emits CO_2 to answer the question, "Does adding CO_2 affect the temperature?" Ms. P had students review the greenhouse effect from day 1 by sketching a **model [SEP-2]** of the **energy flow [CCC-5]** in the **system [CCC-4]** that included solar radiation, infrared radiation, and greenhouse gases (ESS 3.D).

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Ms. P asked students to join her in thinking about factories emitting CO_2 and the essential parts that should be included in the model, reminding them to “keep it simple!” Students decided they wanted to add a factory that emitted a lot of CO_2 while it was operating. Calling on prior knowledge, they decided that the CO_2 should come out of the factory and rise in the atmosphere. As it lingered, it would block heat from escaping and eventually it would be absorbed by growing plants or washed out of the atmosphere (CO_2 dissolves in rain water). Ms. P helped them to see the analogy between releasing CO_2 and creating new agents in their previous models. Then she provided students with a progress monitor that included the following tasks: add a breed for the H_2O factory; use the create-and-do code block to create a factory and position it in the environment; add a breed for CO_2; and give the CO_2 agents new behaviors. After CO_2 had been added, Ms. P guided the students in assigning the CO_2 behavior related to hovering and leaving the atmosphere. She expressed in pseudo-code the description of the behaviors and then asked the students to try their hand at implementing those behaviors. “In the hover procedure, have the CO_2 move upwards a small amount at each time step, until it reaches a height of 12. Once there, it should just move randomly while maintaining the same height. To simulate ways that CO_2 leaves the atmosphere and **cycles [CCC-5]** into other parts of the Earth system, they set a probability that CO_2 would be deleted a small fraction of the time (0.1 percent of the time).” Ms. P reminded the students about the engineering cycle and the need to incrementally make changes and test the model frequently.

To make responding to student questions occur in a timely manner and to develop student self-sufficiency as learners while coding, Ms. P employed three tactics. The first was to use pair programming; the second was to use green, yellow, and red cups for signaling status; and the third was to employ an “ask-three-then-me” method of problem solving. In pair programming, one student played the role of the driver, who wrote code while the other, the navigator, made suggestions and reviewed the code as it was entered. The two programmers switched roles frequently. This practice encouraged communication between members of the pair and collaborative problem solving. Colored cups were useful to quickly take the temperature of the room. Red cups signaled that the students were stuck and could not move forward, yellow cups signaled that the pair was experiencing difficulty but was trying various solutions, and green cups signaled that all was well with the pair. Since the cups were visible to all, students who were ahead could locate and help pairs that were stuck. Finally, the “ask-three-then-me” tactic encouraged students to ask for suggestions from other students rather than running to the teacher for help. When these three tactics were incorporated into the classroom culture, students learned more quickly and became more self-sufficient.

Day 5: Testing and Evaluation of Models (Evaluate)

Investigative phenomenon: The amount of greenhouse gases in the air changes over time.

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To test if their model was working as expected, students added some instrumentation to determine how much CO_2 was in the atmosphere initially and whether or not it declined over time. Once students implemented their code and tested it, students designed an experiment to determine the impact of altering the amount of CO_2 entering the system from the factory.

Ms. P related their work to that of professional scientists who evaluate and test their computer models. First they want to see if the code is doing what they intend or whether it contains bugs (verification). Next, they want to see if running the model produces outcomes that mimic the real-world phenomenon they modeled (validation).

Prior to having the students develop and conduct their own experiment, Ms. P gave an example of an experiment students could conduct: "Run the experiment for 400 ticks without the factory emitting CO_2. Pause the simulation. Write down the temperature from the data box. Then start the factory running and start the simulation running. Now that CO_2 is being emitted, run the simulation for 400 ticks. Pause the simulation and record the temperature. Repeat this process six more times recording the temperature at each 400 ticks." Ms. P showed how students should record the experimental design and data on their experimental design form.

Students then developed and ran their own experiments. They recorded their experiment and findings on a new experimental design form. After they had graphed their model results, Ms. P asked the students if they noticed any **trends [CCC-1]**: "Did temperature increase, decrease, or stay the same over time? What can you say now about the relationship between the production of CO_2 and local temperature?"

After collecting their data, students **communicated [SEP-8]** their experiment and their findings, and proposed an **explanation [SEP-6]** for the **data [SEP-4]**. As they presented their findings, they had to account for any unexpected variations and **construct an argument [SEP-7]** about the **cause and effect relationship [CCC-2]** between CO_2 and temperature (e.g., the production of CO_2 is an important determiner of temperature, increases in CO_2 production turned out to be unimportant, or that an unintended variable interfered with the ability to conclude either way).

Next, she asked students how they could determine whether the outcome of running the model mirrored what was happening in the real world. She led a discussion of how the model was similar to and different from the real world and to what extent a model like this could be used to learn about the real world.

Days 6–7 (optional): Computational Science and Engineering Challenge

Investigative problem: How can we reduce the impacts of human activity on the climate?

This optional two-day extension enabled students to design mitigation strategies [SEP-6] and then implement and test the strategies within a greenhouse gases model to determine their potential impact. Students designed their own alterations to the Greenhouse Gases

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project consisting of a mitigation strategy, a question, an experimental design, and a model. Students isolated and developed their strategy for mitigating CO_2 production (e.g., increase public transportation use, decrease car usage) considering a range of factors (e.g., commuting options, availability of different options in rural vs. urban communities), and identified the changes they would need to make to their greenhouse gases model. This led to a second activity in which they designed and implemented their model, then used the model as an experimental testbed to assess the impact of the mitigation strategy they proposed.

Vignette Debrief

Computer models provide a complete framework for teaching science. With computational modeling and simulation, students are able to ask "what-if" **questions [SEP-1]**. They act as both theorists and experimentalists. When students **develop models [SEP-2]**, they have to think about the underlying processes. The models allow students to **plan and conduct investigations [SEP-3]** that test and isolate different **cause and effect relationships [CCC-2]**. Because models run quickly, students could obtain a large amount of data to **analyze [SEP-4]** for **patterns [CCC-1]**. The models also serve as a focal point for **argument based on evidence [SEP-7]**. Students have to address the limitations of the model, the assumptions made, and work together to determine the explanatory power of the model. Throughout this vignette, Ms. P promotes meta-thinking about the nature of models. She encourages skepticism and dialog by asking, "In what ways did it reflect the real world? In what ways was it lacking?" and "Would you trust this model if your life depended on it?" Students describe how they would decide if the model were realistic enough to be used to make predictions of the future.

SEPs. Students perform two **investigations [SEP-3]** of the impact of increasing CO_2 production on local temperature at a range of **scales [CCC-3]**, they **ask questions [SEP-1]** about what would be the impact of adding new sources of CO_2. They **analyze their data [SEP-4]** to help figure out the relationship between different components in the **system [CCC-4]** they studied. They use these relationships to **analyze a model [SEP-2]** of the system. They use the data from their investigations along with the reasoning of their model to **construct an explanation [SEP-6]** about the **causes [CCC-2]** of climate change. In the Computational Science and Engineering design challenge, they employ engineering practice by **defining the parameters of the problem [SEP-1]** and **designing solutions [SEP-6]**. They then created a compelling **argument [SEP-7]** that their design was an effective way to mitigate human impacts on local temperature. Students briefly explore the results of their **computational science [SEP-5]** projects that investigate mitigation strategies to combat climate change.

DCIs. The greenhouse gas effect is a tangible example of human impacts on Earth systems (ESS3.C) and a microcosm of the entire energy balance in the global climate system (ESS2.D). Students begin to characterize variations in Earth materials (reflectivity) and the impact of these variations (ESS2.A), then explore the role of human behavior in Earth's systems. This vignette extended part way into the high school level of understanding of global

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climate. In the middle grades, students are supposed to ask questions about what causes temperature changes, but they are not to be assessed about the details of the greenhouse effect until high school.

CCCs. Students apply the crosscutting concept of **systems and system models [CCC-4]** to represent the **flow of energy [CCC-5]** and the interactions between energy and matter. Students look for **patterns [CCC-1]** in temperature **data [SEP-4]** to test for **cause and effect [CCC-2]** relationships between CO_2 production and local temperature. They learn to question the validity of the **model [SEP-2]** and consider what it can and cannot tell us about the real world. Feedback loops provided an example of where the line between **cause and effect [CCC-2]** blurs. While feedback loops are essential for a complete understanding of Earth's climate, feedback mechanisms are a high school level of understanding of CCC-2 that goes beyond the baseline level expected of middle grade students.

EP&Cs. Climate change affects the welfare of humans in their everyday lives, and students discover that some of the potential solutions to the problem involve changes in human behavior (EP&C I, II). The bulk of the modeling focuses on understanding Earth's cycles and how humans alter them (EP&C III). On days 6–7, students really dig into the complexity of solutions (EP&C V).

CCSS Connections to English Language Arts and Mathematics: Throughout the vignette, students participated in several small-group and whole-class discussions (SL.6–8.1a–d, 4, 5). They gathered information from several sources (RST.6–8.3, 9) to make scientific arguments supported by evidence (WHST.6–8.1). Coding provided an excellent example of reasoning quantitatively (MP.2) and modeling using mathematics (MP.4). The students participate in a coding exercise and simulation to answer the question "Does adding CO_2 affect the temperature?" (7.RP.2c-d).

Resources

Several of the activities described in this vignette were adapted from other sources and are cited within. Please refer to them for more detail.

The Project GUTS Introduction to Computer Modeling and Simulation module is available at https://www.cde.ca.gov/ci/sc/cf/appx3.asp#link6.

The Project GUTS Climate Change module is available at https://www.cde.ca.gov/ci/sc/cf/appx3.asp#link7.

Historical temperature data can be viewed https://www.cde.ca.gov/ci/sc/cf/appx3.asp#link8.

See the Intergovernmental Panel on Climate Change (IPCC) document "Climate Change 2007: The Physical Basis" for details of the 24 different climate models used to study climate change.

For more information on climate change, go to the Web site: https://www.cde.ca.gov/ci/cf/appx3.asp#link9.

The Online Carbon Footprint Calculator is available on the EPA Web site: https://www.cde.ca.gov/ci/sc/cf/appx3.asp#link10.

High School Life Science Vignette: Ecosystems as Complex Systems

HIGH SCHOOL LIFE SCIENCE COMPUTER SCIENCE VIGNETTE APPENDIX 3.2: ECOSYSTEMS AS COMPLEX SYSTEMS IN HIGH SCHOOL

By Irene Lee, Director, Project GUTS, Research Scientist, MIT Scheller Teacher Education Program/Education Arcade

Performance Expectations

Students who demonstrate understanding can do the following:

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

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

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

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

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

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

HS-ETS1-4. 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.

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Highlighted Science and Engineering Practices	**Highlighted Disciplinary Core Ideas**	**Highlighted Crosscutting Concepts**
[SEP-1] Asking Questions and Defining Problems [SEP-5] Using Computational and Mathematical Thinking [SEP-6] Constructing Explanations and Designing Solutions [SEP-7] Engaging in Argument from Evidence	LS2.A Interdependent Relationships in Ecosystems LS2.C Ecosystem Dynamics, Functioning, and Resilience LS2.D: Social Interactions and Group Behavior ETS1.A: Defining and Delimiting Engineering Problems ETS1.B: Developing Possible Solutions	[CCC-2] Cause and Effect: Mechanism and Explanation [CCC-3] Scale, proportion, and quantity [CCC-4] Systems and System Models [CCC-7] Stability and Change Connections to Engineering, Technology, and Applications of Science Influence of Science, Engineering, and Technology on Society and the Natural World

Significant Connections to California's 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.

CA CCSS Math Connections: S-IC.1,2,5,6

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

CA CCSS for ELA/Literacy Connections: SL.9–12.1a–d,4,5; RST.9–12.3,9 WHST.9–12.1

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Introduction

This life science vignette begins with an exploration of a simple predator–prey model to consider who eats whom—and what happens when one population grows faster than another. The goal of this vignette is to make these concepts come to life through computer modeling and simulation and develop a better understanding of ecosystem dynamics by acting as computational scientists. After learning more about ecosystem dynamics, producers and consumers, and interdependent relationships within an ecosystem, students develop their own model of a local ecosystem. As students use, modify, and create an agent-based model of a simple virtual ecosystem, they deepen their understanding of ecosystems concepts. As in many scientific endeavors, the students are challenged to be precise with their scientific language, to be explicit in describing their conceptual models, and to revise their models as new evidence is produced. As computational scientists, students learn to represent conceptual models by decoding, using, modifying, and creating computer models. As students gain experience with computational thinking, modeling and simulation, and data analysis—scientific practices key to the CA NGSS—they gain better understanding of the DCIs and CCCs.

Length and position in course. This vignette describes one week of instruction based on Project GUTS' Computer Science in Science module on Ecosystems. This module describes how computer models can be developed, used, and analyzed in the context of studying ecosystems as complex systems. Teachers need to select an anchoring phenomenon related to ecosystem dynamics in their local habitat, such as a news article about a recent increase in neighborhood coyote sightings or a sudden decrease in butterfly migration.

Prior knowledge. This lesson assumes that the teacher had already introduced ecosystems concepts such as (a) the definition of an ecosystem, (b) indirect interactions within ecosystems, (c) direct interactions between organisms in ecosystems, (d) food chains and food webs, (e) energy flows in ecosystems, (f) trophic levels, and (g) biomass in ecosystems. It is necessary to have completed the six-day sequence introducing computer modeling and simulation (such as module 1 of the Code.org *Computer Science in Science* curriculum) prior to commencing this module so that students have the necessary skills to perform the modeling required in this module. Students need basic skills in reading and modifying computer codes. They need to interpret an existing base model and make modifications to it by adding new codes or altering the ones that exist. While this vignette provides opportunities to practice those skills, they are not specifically addressed in this lesson outline.

Teacher background. Ecosystems as complex systems.

One of the main characteristics of a complex system is that the behavior of some aspects of the system, seen as a whole, does not necessarily follow directly from an understanding of how the individual "parts" of the system work. Another characteristic of most complex systems is feedback: as the system changes, the new state of the system affects the way in which the system changes in the future. For example, if we look at the ecosystem of fish in a pond where fish are not being consumed by predators, we see that as the population approaches the carrying capacity of the pond, the rate of eggs hatching and maturing to adulthood decreases. This is often through increased cannibalism as other food sources become scarce; it also

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happens when other required resources are limited (e.g., oxygen in the water). So the increase in the fish population leads to a reduction in the necessary resources available to each member of the population, which in turn leads to moderation in the rate of increase in the population. (This type of feedback is called a balancing feedback in this framework.) This interaction balances the change and causes the population growth curve to stabilize.

Another important feature of complex systems is that relationships are nonlinear: small changes at one moment may result in disproportionately large changes later on. Ecosystems often demonstrate this feature: we might have relative stability in the populations of a number of species, but then a brief spike or dip in one can produce a chain reaction of changes in the other populations, sometimes with serious results. Possibly most important, ecosystems often demonstrate emergent behavior. This is related to the first point, where the overall behavior turns out not to be obvious from the component behavior. In an aquatic ecosystem, simply knowing that fish eat plankton and shark eat fish does not tell us much (beyond giving us a general sense) about the patterns in the respective populations over time—we really need to study the ecosystem as a whole. This illustrates that ecosystems are usually complex systems, as well.

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

Day 1: Introduction to Ecosystems as Complex Systems (Engage)

Students experienced population growth and limits to growth through a participatory simulation that reinforces the ecosystem concept of a carrying capacity. Then students previewed a simple ecosystem model and tried to maintain artificial populations within the modeled ecosystem.

Day 2: Decoding and using the Rabbits and Grass Base Model to Run Experiments (Explore)

Students inspected the Rabbits and Grass model to learn about the implementation of behaviors and energy cycling through the modeled ecosystem. Then the students designed and ran an experiment of their choice.

Day 3: Modifying the Base Model and Investigating the Impact of Changing Variables on the Ecosystem. (Explain)

Students experiment with changing either the initial population sizes or the energy cycling through the ecosystem and witnessing the impact the change has on the longevity of the populations within the ecosystem.

Day 4: Adding a Top Predator to the Model and Running an Experiment (Extend)

Students added a top predator to the modeled ecosystem and designed an experiment to investigate the impact of the addition on existing populations. Then they used their models to run controlled experiments and tracked the outcomes of subsequent runs of the model.

Day 5: Testing and Evaluation of the Model (Evaluate)

Students considered whether their models were working and reflect the real-world phenomenon of ecosystem dynamics.

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Days 6–7 (Optional): Student symposium

Students prepared and gave presentations on their models, questions, experimental design, and findings in a symposium-like setting. They were encouraged to ask each other to show a part of their code that they were proud of and made the case for their conclusions based on their model and findings.

Day 1: Introduction to Ecosystems as Complex Systems (Engage)

Investigative phenomenon: In a kinesthetic model, population changes as resources change.

Ms. E grounded students' understanding of population dynamics and carrying capacity through a **kinesthetic model [SEP-2]** called "Papercatchers." She informed the class that they would play the part of members of a growing population and experience limits to the growth of populations when resources were limited. Ms. E asked for a volunteer recorder to set up a graph on the whiteboard with the x-axis labeled with generations #1 through #10 and the y-axis labeled with population size between 0 and 50.

Round one began by having each student crumple up a piece of paper from the recycle bin into a ball. Ms. E picked one student to represent the initial member of the population and asked that person to stand in the middle of the room. The recorder marked the graph with generation 0 having population size of 1. Ms. E told her class that after she gave the "next generation" command, the population member(s) were to throw the paper ball two feet overhead and attempt to catch it. If the population member succeeded, then they survived into the next generation and reproduced by selecting a student from the audience who was not already part of the population to join in the population. If they did not catch the paper ball, they did not survive and had to sit down.

At each generation, the recorder updated the graph with the new population size. Ms. E had the students repeat this process for several more generations. One time the population crashed or became extinct, so they began again with one population member, noting that sometimes populations crash by chance when numbers are small. Once all members of the class were standing, she gathered them around to take a look at the graph. The recorder summarized the data and students reflected on the **pattern [CCC-1]**. Ms. E asked, "Was this what you expected? What type of pattern do you see? What do you predict would happen if we could play with an unlimited number of people?" (The result would be exponential growth/ population explosion.)

Next, Ms. E told the class that they were going to play with slightly different rules in round two. She unfolded a single piece of newspaper and placed it on the floor. She told the students there was an added constraint. To survive, they had to throw and catch their paper ball while keeping one foot on the piece of newspaper at all times. Ms. E asked for predictions

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of what would happen when they played this round. She also asked for a new student to act as recorder. The new recorder made the population size and generation number as before, but in a different color marker. Ms. E led the class through several generations and (after the population size stabilized) asked students what pattern they observed in the data and how the piece of newspaper related to limited resources in nature. Ms. E helped students make the connection between the piece of newspaper and a limited food supply (LS2.A). She drew a horizontal line across the graph at the maximum population supported by the piece of newspaper and called it the carrying capacity. (The S-curve in the data is known as Logistic Growth.)

Finally, before round three, Ms. E told the class that the piece of newspaper would be replaced with a sheet of paper 8.5 by 11 inches. She asked students for a prediction of what would happen when they played again. Where would the line marking the carrying capacity be under these conditions? For this round, Ms. E asked the recorder to use a different colored marker. Play ensued for several generations (with much laughter), and the carrying capacity of the smaller sheet of paper was determined. Ms. E concluded the activity with a discussion on the relationship between food supply and population growth and related it to the need to feed the world's growing population. Several students identified another potential application of the model: investigating how the health of an ecosystem would influence human efforts to increase the food supply for the human population (EP&C I).

Investigative phenomenon: In a computer model, a rabbit population quickly grows until it suddenly crashes.

Next, Ms. E opened the StarLogo Nova base model of an ecosystem consisting of rabbits and grass and used the projector to introduce it to students. She demonstrated how to use the "setup" and "run forever" buttons to reset and run the model. Ms. E asked students to tell her what to do next and to interpret what they were seeing when the model was run. She asked, "What are the components in this model?" and heard that the model contains earth, rabbits, and grass. Ms. E asked, "When the model runs or is 'executed' what happens?" and heard various **interpretations [SEP-4]** of the results, ranging from "The bunnies multiply out of control" or "All the grass gets eaten" or "The system **collapses [CCC-7]**." After the model had been run several times and the **pattern [CCC-1]** of population growth and crash compared using the model, Ms. E asked the students to summarize the sequence of events. "The rabbits eat grass and multiply, then the population of rabbits grows and eats all the grass, then all the rabbits die." Ms. E asked the students if the pattern was the same every time the model was run. Some students noticed that result of each run of the computer model was slightly different. For example, a few times the population grew more slowly. This observation led to a discussion of what computer models are good for and how they can help us understand ecosystem dynamics.

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Day 2: Decoding and Using the Rabbits and Grass Base Model to Run Experiments (Explore)

In the first activity of this lesson and before they inspected the model's code, the students reviewed familiar code blocks. Ms. E assigned partners to work together and then assigned each pair a segment of the model's code to examine and decode: a "model observation form" was used to document what each of the assigned procedures did to produce the behavior of the rabbits, grass, or "the world." After five minutes of decoding, Ms. E asked the students to share their findings. Following each pair's reporting about what mechanisms or behaviors were implemented in the algorithms, Ms. P asked students if they had other interpretations of what the code did. Any dissension was resolved by **looking closely at the source for evidence [SEP-7]**—the code itself. Ms. P concluded the activity by discussing the main program loop and execution order. She had students draw a diagram mapping the sequence of procedures and sub-procedures. She then had students enact their diagram as a physical model with pairs of students moving around the room from one procedure to the next to the next to simulate the execution of the code, starting with the pressing of the setup button.

Day 3: Modifying the Base Model and Investigating the Impact of Changing Variables on the Ecosystem. (Explain)

In the first activity of this lesson, students learned how to use the model to run an experiment by changing either the variable related to initial population size of grasses or energy gained from eating. Ms. E asked the students what happened in the model when a rabbit ate grass. A student responded, "The grass disappears and the rabbit gains energy." Ms. E asked if this was realistic and followed with the question, "Do you think that the amount of initial grass in the ecosystem determines how long the rabbits will survive?" Ms. E asked students to write down their prediction. Some students answer yes while others answered no. Ms. E prompted students to engage in **argumentation based on evidence [SEP-7]**. Some students used the reasoning that the population would survive if there were enough grass to start with, while others reasoned that the population would just explode faster.

Investigative phenomenon: The rabbit population grows at a different rate when there is more initial grass in the model.

Next, students were asked to locate this variable in the code that controlled the initial amount of grass, change the variable to reflect a different initial population, and run the model again. After a few minutes, Ms. E asked the students to crowdsource their data and report the value they chose and the outcome in terms of how long the ecosystem persisted. **Analyzing [SEP-4]** the amassed data, Ms. E asked the students if they noticed any difference when they ran their model this time and whether their prediction was correct.

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Investigative phenomenon: The rabbit population grows at a different rate when each clump of grass provides more energy to the rabbits.

Students added new computer code creating a slider on the user interface panel that allowed them to easily set the amount of energy the rabbits got each time they ate the grass. Then, students posed **questions [SEP-1]** about the **effect [CCC-2]** of changing this variable and reflected on the real-world implications of their discoveries. A graphic organizer Ms. E called an "experimental design form" guided students as they developed scientific questions they could investigate using their model. Through scaffolding, the form helped students see the need to use trials and to clearly identify the variables. Students, working in pairs, specified which variable they would change, then designed and ran their experiment. Within what range did the variables fall? How many trials were done each setting? They used the instrumentation in the model (the graph and the data boxes) to monitor temperature under the different scenarios. Students recorded the data from the graph. Then they **analyzed [SEP-4]** the results of their experiments, documented the **patterns [CCC-1]** in their findings, and used these as evidence to support a claim **explaining [SEP-6]** one aspect of the system.

Finally, students extended the model based on what they had learned about ecosystems, **energy flows [CCC-5]** within ecosystems, interactions within ecosystems and how human activities influence ecosystems. Ms. E led a wrap-up discussion about models and modeling. In what ways might this model be helpful to scientists in understanding ecosystems? Might this model help scientists predict the effects of human activities on ecosystems? How would a scientist determine if their models were accurate enough to make predictions?

Day 4: Adding a Top Predator to the Model and Running an Experiment (Extend)

Investigative phenomenon: Adding predators to the model changes the growth rate of the rabbits.

Ms. E started off day 4 by asking students what they would predict as the effect of adding a top predator to the model. Then Ms. E led reviews of what they learned in previous computer science lessons about how to add a new agent to their model—first she demonstrated how to add a new "breed" of agents using the "add-breed" widget, then she noted that students could simply refer to how rabbits are given behaviors when setting up behaviors for a new agent. She then asked students what the top predator would eat and how much energy it would gain each time it ate. Students proposed that the predator eats rabbits, acquiring all the rabbit's energy, but Ms. E asked students to think about the energy conversion process. No energy conversion is 100 percent efficient. Developing a model allows students to discover the concept of trophic levels—they had to think very specifically about how to represent the energy transfer within the ecosystem (LS2.B). Ms. E then let the

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students go to work on modifying the rabbits and grass ecosystem base model by adding a top predator to answer the question, “Does adding a top predator affect the longevity of the ecosystem?” Ms. E reminded the students about the engineering cycle and the need to incrementally make changes and test the model frequently.

To respond to student questions in a timely manner and to develop student self-sufficiency as learners while coding, Ms. P employed three tactics. The first was to use pair programming; the second was to use green, yellow, and red cups for signaling status; and the third was to employ an “ask-three-then-me” method of problem solving. In pair programming, one student played the role of the driver, who wrote code while the other, the navigator, made suggestions and reviewed the code as it was entered. The two programmers switched roles frequently. This practice encouraged communication between the pair and collaborative problem solving. Colored cups were useful to quickly take the temperature of the room. Red cups signaled that the students were stuck and could not move forward, yellow cups signaled that the pair was experiencing difficulty but was trying various solutions, and green cups signaled that all was well with the pair. Since the cups were visible to all, students who were ahead could locate and help pairs that were stuck. Finally, the “ask-three-then-me” tactic encouraged students to ask for suggestions from other students rather than running to the teacher for help. When these three tactics were incorporated into the classroom culture, students learned faster and became more self-sufficient.

Ms. E instructed students to test their models. To test if their model was working as expected, students needed to add some instrumentation to log the size of each population over time and visualize the balance of species in the ecosystem. Once students had implemented their code for output data boxes and plots of population sizes, students had to **plan an investigation [SEP-3]** to determine the impact of adding the top predator. Students recorded their ideas and findings on a new experimental design form. After students had graphed the data points, Ms. E asked the students if they noticed any trend: “Did the ecosystem last for a longer or short duration with the addition of the top predator? What can you say now about your testable idea?” She wrapped up the activity with a discussion of energy flow and why a population might persist longer with the existence of a top predator. To extend students’ thinking further, Ms. E asked students to propose ways that they could modify their models to include human activities (EP&C II).

Day 5: Testing and Evaluation of Models (Evaluate)

In this lesson, Ms. E asked students to think about how they would test to see if their models were “correct.” She explained that there were two concerns: (1) whether the coding was done properly and (2) whether the model included the right elements. To test whether the coding was done properly, students traced their code and worked through the program logic in pairs. The difficulty of testing was discussed because the randomness inherent in agent-based models means that no two runs of the model would produce identical outcomes. Since that was the case, how would they discern whether their code was written correctly?

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Ms. E reassured the class that they could test specific cases with known outcomes to make sure that the outcomes were produced as expected. The class came up with a few situations that had obvious outcomes such as very little grass or many more consumers than producers. Next, Ms. E asked half the students to **support an argument [SEP-7]** that their models represented real-world ecosystems and the other half of the students to support an argument that their models do not represent real-world ecosystems. She encouraged them to think about what they knew of the real-world populations and interactions. Several students pointed out that they couldn't really know for sure because they did not have real-world data to compare the models' output to. Ms. E pointed out that their models and experiments still had value—the students learned to identify **trends [CCC-1]** and connect outcomes to patterns of population growth and decline.

Days 6–7 (Optional): Student Symposium

After collecting and analyzing their data, students presented their experiment and findings and proposed an **explanation [SEP-6]** for the **data [SEP-4]**. As they presented their findings, they had to account for any unexpected variations and **construct an argument [SEP-7]** supporting one of these findings: the addition of a top predator was a determiner of longevity of the ecosystem; the addition of a top predator turned out to be unimportant; or that an unintended variable interfered with the ability to conclude either way. Then students prepared presentations that took place at the next class meeting. Each team of students gave a five-minute presentation following these guidelines:

1. State the question you were seeking to answer.
2. Present any background research you did on the topic.
3. Tell us about your model (what's included and what was left out).
4. Tell us about your experimental design.
5. Show your model running and how you collected data.
6. Show any collected data and how it was analyzed.
7. Tell us about any relationships you noticed between variables that help you understand or predict the phenomenon.
8. Summarize your findings; what was the outcome of running your experiments?
9. Do you think you learned anything about the real world?
10. Show us a piece of code you are most proud of.
11. Allow time for questions and answers.

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Revisiting the Model (Optional)

Investigative phenomenon: Rabbits with different traits become more common within the population over time.

A few weeks later when the class was exploring evolution, Ms. E revisited the model. Rather than hypothetically arguing whether or not variation in a population had to exist before selection could act, students could modify computer models to try different scenarios, such as comparing the effects of human activities on the rate of environmental change and how that affects different populations (EP&C II). In one model, all the individuals would have the same genetic characteristics, and in the other model individuals would have varying traits. When a predator was introduced, certain characteristics were more favorable than others. When simulations were run over multiple generations, students could determine how the population changed over time and could argue whether or not variation was necessary before selection could act. Note that in the course of making this model and implementing reproduction and predation, students needed to review and program the inheritance of traits (LS3.A) and energy flow through an ecosystem (LS2.B). Ms. E used the model to help her students meet HS-LS4-3 ("Apply concepts of statistics and probability to support explanations that organisms with an advantageous heritable trait tend to increase in proportion to organisms lacking this trait") and HS-LS4-4 ("Construct an explanation based on evidence for how natural selection leads to adaptation of populations").

Vignette Debrief

Computer models provide a complete framework for teaching science. With computational modeling and simulation, students are able to ask **"what-if" questions [SEP-1]**. They act as both theorists and experimentalists. When students **develop models [SEP-2]**, they have to think about the underlying processes. The models allow students to **plan and conduct investigations [SEP-3]** that test and isolate different **cause and effect relationships [CCC-2]**. Because models run quickly, students can obtain a large amount of data to **analyze [SEP-4]** for **patterns [CCC-1]**. The models created also serve as a focal point for **argument based on evidence [SEP-7]**. Students have to address the limitations of the model, the assumptions made, and work together to determine the explanatory power of the model. Throughout this vignette, Ms. E promotes meta-thinking about the nature of models. She encourages skepticism and dialog by asking, "In what ways did it reflect the real world? In what ways was it lacking?" and "Would you trust this model if your life depended on it?" Students have to describe how they would decide if the model were realistic enough to be used to make predictions of the future.

The goal of engaging students in modeling is not just one of developing their understanding of the concepts of science. Rather, it is to also learn a form of meta-knowledge about science—that is knowledge of specific features of science and their role in contributing

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to how we know what we know. For instance, when students construct models, it helps them to understand that the goal of science is not the construction of a picture that accurately depicts every aspect of nature, but rather a map that captures some certain important features and not others. In developing models, students should propose an explanation of a particular process or phenomenon by focusing their attention on key aspects of the system and the variables that are relevant to that process, while de-emphasizing other details which are less relevant at that moment but may be reconsidered later.

The structure of lessons that incorporate both on- and off-computer activities and building student understanding over time by activating prior knowledge is useful for extending that prior knowledge through new experiences. The time spent using the computer is scaffolded by a "Use-Modify-Create" framework in which students begin by using the model, then make small modifications, and finally create entirely new components.

SEPs. Students perform **investigations [SEP-3]** on the impact of modifying the **energy flow [CCC-5]** through the modeled ecosystem; then they **ask questions [SEP-1]** about the impact of adding a top predator. They **analyze their data [SEP-4]** to help figure out the relationship between different components in the **system [CCC-4]** they studied. They use these relationships to **analyze a model [SEP-2]** of the system. They use the data from their investigations along with the reasoning of their model to **construct an explanation [SEP-6]** about the **causes [CCC-2]** of ecosystem collapse. In the Student Symposium, they employ the engineering practice of creating a compelling **argument [SEP-7]** that their findings were true to life.

DCIs. Organisms, and populations of organisms, are dependent on their environmental interactions both with other living things and with nonliving factors (LS2.A). In this vignette, students model only the interactions between living parts of the ecosystem. They explore the carrying capacity and stability of ecosystems under different conditions (LS2.C).

CCCs. **Patterns [CCC-1]** can be used to identify **cause and effect [CCC-2]** relationships. Cause-and-effect relationships may be used to predict phenomena in natural or designed systems. Students have to make sure that their model tracked the **energy flows [CCC-5]** through the natural system; they confront this problem explicitly when they think about how much energy the predator received when eating a rabbit. Their models also illustrate how populations **change and move towards stability [CCC-7]**. Students discover the surprising effect that adding a predator actually helped prevent the rabbit population from crashing.

EP&Cs. The dependence of human populations on healthy natural systems as well as the influence of human societies on those systems offers a variety of opportunities for students to engage in computational thinking, modeling and simulation, and data analysis. Computer models like those used to analyze changes to Earth's climate are frequently the only means through which scientists and students can predict the long-term impacts of humans on natural systems and changes to natural systems on humans. In this vignette, students propose different ways that they could represent human impacts in their models. In the process, they have to think carefully about the specific **mechanisms [CCC-2]** by which humans alter natural

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cycles (EP&C III). Students have to think about how they would represent diverse human behaviors such as polluting, hunting, destroying habitat through deforestation, or disrupting habitat through building roads that divide populations.

CA CCSS Connections to English Language Arts and Mathematics. Throughout the vignette, students participate in several small-group and whole-class discussions (SL.9–12.1a–d, 4, 5). Students participate in a computer simulation that comprises an ecosystem of rabbits and grass. The students run the simulation looking for patterns in the data. Students argue (WHST.9–12.1) whether changing a variable (the amount of initial grass) would change the outcome of the simulation. The students also add a top predator to the model and graph data points and analyze what impact the top predator made on the rabbit population (S-ID.1,2,5,6).

Resources

Several of the activities described in this vignette were adapted from other sources and are cited within. Please refer to them for more detail.

The Project GUTS Introduction to Computer Modeling and Simulation module is available at https://www.cde.ca.gov/ci/sc/cf/appx3.asp#link11.

The Project GUTS Ecosystems module is available at https://www.cde.ca.gov/ci/sc/cf/appx3.asp#link12.

High School Earth and Space Science Vignette: Water Resources and Farming

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By Irene Lee, Director, Project GUTS, Research Scientist, MIT Scheller Teacher Education Program/Education Arcade

Performance Expectations

Students who demonstrate understanding can do the following:

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

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

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

HS-ETS1-4. 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.

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Highlighted Science and Engineering Practices	**Highlighted Disciplinary Core Ideas**	**Highlighted Crosscutting Concepts**
[SEP-1] Asking Questions and Defining Problems [SEP-4] Analyzing and Interpreting Data [SEP-5] Using Computational and Mathematical Thinking [SEP-6] Constructing Explanations and Designing Solutions	ESS3.A: Natural Resources ESS3.B: Natural Hazards ESS3.C: Human Impacts on Earth Systems ESS3.D: Global Climate Change ETS1.A: Defining and Delimiting Engineering Problems ETS1.B: Developing Possible Solutions	[CCC-2] Cause and Effect: Mechanism and Explanation [CCC-4] Systems and System Models [CCC-7] Stability and Change Connections to Engineering, Technology, and Applications of Science Influence of Science, Engineering, and Technology on Society and the Natural World

Significant Connections to California's 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 IV The exchange of matter between natural systems and human societies affects the long-term functioning of both.

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

CA CCSS Math Connections: S-IC.1,2,5,6

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

CA CCSS for ELA/Literacy Connections: SL.9–12.1a–d,4,5; RST.9–12.3,9 WHST.9–12.1

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Introduction

This Earth Science vignette considers how humans are impacting the environment and how resources are being used and managed (or not managed) for the future. Students model the hydrological cycle as a complex system that includes humans that consume water resources. In particular, the Project GUTS Computer Science in Science Earth Science module explores groundwater as a shared resource and factors that affect how a resource is shared among stakeholders. Even though water continually cycles among land, ocean, and atmosphere, humans use some water resources that are not renewable or replaceable over human lifetimes. As human populations increase, the consumption of natural resources increase, and so do the negative impacts on Earth.

The base model for this unit simulates the part of the hydrological cycle in which water drops as rain, seeps into an aquifer, and is pumped out by a single pump. Students walked through each part of the model, ran experiments to better understand the model, and then modified the base model to add additional pumps and/or add variable rates for rainfall, pumping, and infiltration (soil types). Students then modify this model to explore different changes to the system.

Length and position in course. This vignette describes one week of instruction based on Project GUTS' Computer Science in Science module on Water Resources. This module describes how computer models can be developed, used, and analyzed in the context of studying human impacts on Earth's systems.

Prior knowledge. This Earth Science module offers some disciplinary core concepts through direct instruction and activities but assumes the students already possesses a certain level of knowledge in key areas. Concepts such as the hydrological cycle, watersheds, surface water, ground water, precipitation, percolation, aquifers, porosity, and infiltration are reviewed; but in order to achieve deeper learning, it is advisable that the students will have covered these concepts beforehand. A recommended video that introduces these concepts is available at https://www.cde.ca.gov/ci/sc/cf/appx3.asp#link13. An alternate video is available at https://www.cde.ca.gov/ci/sc/cf/appx3.asp#link14.

This vignette assumes that students have completed a multi-day sequence introducing computer modeling and simulation (such as module 1 of the Code.org CS in Science curriculum). Students need basic skills in reading and modifying computer codes. They need to be able to interpret an existing base model and make modifications to it by adding new codes or altering the ones that exist. While this vignette provides opportunities to practice those skills, they are not specifically addressed in this lesson outline.

Teacher background

California is the largest agricultural producer in the country. Its farming success depends on three main natural resources: its climate, fertile soil, and the availability of massive amounts of water for irrigation. Agriculture is by far the number one user of developed water (more than 75 percent of all consumed water). The state gets its water from a combination

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of groundwater pumping (20-40 percent, depending on the year; Legislative Analyst's Office 2010) and surface water from rivers and reservoirs. Articles about California's water supplies, along with some hands-on demonstrations of the groundwater storage capacity of different Earth materials, can serve as valuable review of these topics.

Students build on their model of the hydrological cycle in the middle grades (MS-ESS2-4). The high school performance expectations from the CA NGSS did not add any additional content knowledge tasks related to the internal processes of the hydrosphere. Instead, they press students to apply the knowledge from previous grades to situations involving hydrosphere-anthrosphere interactions (EP&C Principles I, II, & III).

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: Introduction to Water as a Shared Resource (Engage)

Students engage in a discussion about water resources stimulated by a video and a participatory simulation where they play the role of various water users. The activities provide background and a common basis necessary for further exploration of water resources and how communities make decisions.

Day 2: Decoding and using the Water Pumping Base Model to Run Experiments (Explore)

After reviewing math basics for modeling, students are introduced to the base model. They examine and decode the computer model and interpret what mechanisms are implemented. Then they run the model to conduct a simple experiment.

Day 3: Modifying the Base Model and Investigating the Impact of Changing the Evaporation Rate (Explain)

Students add an evaporation slider and design an experiment to investigate the impact of evaporation on water availability. Then they use the model to run experiments by changing the evaporation rate in subsequent runs of the model.

Day 4: Adding water Pumps to the Model and Running an Experiment (Extend)

Students extend their models to include other users with water pumps drawing from the same aquifer then run experiments to determine the impact on the availability of water.

Day 5: Testing and Evaluation of the Model (Evaluate)

Students consider whether their models are working and reflect the real-world phenomenon of water sharing in a community of users.

Days 6–7 (Optional): Computational Science & Engineering Challenge

Students design potential sharing strategies or policies and implement them in their model. They test the strategy within the model and examine its impact.

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Day 1: Introduction to Water as a Shared Resource (Engage)

Anchoring phenomenon: People in some parts of the world must travel great distances to get clean drinking water.

Ms. H engaged students by contrasting the availability of clean water in the United States with other parts of the world. She showed *Water for Life: Diary of Jay-Z in Africa,* a video (found at https://www.cde.ca.gov/ci/sc/cf/appx3.asp#link15) that got students thinking about water resources and the difficulties some people their age face in obtaining safe drinking water. Ms. H asked students to think about why groundwater from wells can be safer than water that flows at the surface. She asked students to **draw models [SEP-2]** that tracked the **cycling [CCC-5]** of water and how pollution could be carried along the surface but filtered out by the soil that holds groundwater. She used the models to get students to realize that the groundwater beneath their feet is connected to the groundwater beneath their neighbors. In other words, we all depend on a shared resource.

Investigative phenomenon: When people rely on a shared resource, they may try to hoard too much of the resource for themselves and ultimately deplete the resource for everyone (including themselves).

Ms. H wanted students to consider some of the issues that arise from sharing resources. She had students engage in a **kinesthetic model [SEP-2]** called “Some for All or All for One,” which highlighted some of the interesting dynamics that come about when a group of individuals has to make decisions regarding a shared resource. Students acted as stakeholders in a water-sharing scenario. Each individual in the simulation had the ability to choose what amount of the resource they took based on some simple rules. When considering a shared resource like water from a well, students were aided by this activity to understand that each member in a community who used this well had an impact on every other community member. After the activity, Ms. H asked how students made their decisions and if there were any unexpected results. Then she led a short debrief incorporating evidence on the evolution of human cooperation (for more details, see the following articles: https://www.cde.ca.gov/ci/sc/cf/appx3.asp#link16 and https://www.cde.ca.gov/ci/sc/cf/appx3.asp#link17).

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Making decisions as an individual or as a group can often lead to unexpected results. If you were to study the "average" decision that individuals make, it would not always be a good predictor of what the group as a whole would decide. Individuals may act differently when they are cooperating. In small groups, humans will often cooperate because they are related to or friends with the others in the groups. Cooperation and sharing resources was necessary for our human ancestors' early survival, yet cooperation still exists today. There are not many "free loaders"; people in groups tend to help out and eventually are rewarded when they receive help from others. There are many examples of cooperation by humans—a group of hunters going after a large prey, cooperating on the playing field to win a game, community gardens and farms, volunteering to help pass out papers in the classroom, etc. However, even if cooperation is still common in humans, it doesn't mean that everyone in a group will cooperate with a group decision. In this case, an individual could "defect" from the cooperation yet still benefit from the resources that are in the community. In a group of cooperative people, it is often beneficial for a person to act in a selfish way.

Day 2: Decoding and Using the Water Pumping Base Model to Run Experiments (Explore)

To build up programming skills and motivate students to review the mathematics necessary to understand the base model, Ms. H started the day with a set of simple programming challenges. Students had to position agents in the virtual world (Spaceland). Students then entered instructions for the turtles to move to certain locations using relative and absolute directions to review Cartesian coordinates and turtle motion and positioning in StarLogo Nova. In a second activity, Ms. H asked students to get out their StarLogo Nova blocks reference guide and use it in decoding the base model of a water pump. In small groups, students kept track of new and familiar blocks encountered as they decoded a segment of code. Ms. H asked each group to report on what their group's assigned piece of code did. Ms. H then drew an illustration of the "runtime loop" and asked students to call out all of the things that were updated each time the computer executed the loop. She added the student suggestions of the updated items to the diagram (such as update agents, or draw the screen), or addressed preconceptions about how the parts of the code are executed.

Investigative phenomenon: When a well pumps, the water level near the well is much lower so that it looks like there is a "cone of depression" shape around the well opening.

With this understanding of the model, students ran it and simply observed the outcome. After running the model several times and comparing the distribution of groundwater produced by running the model, Ms. P led the students in developing a statement that

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described the **pattern [CCC-1]** of how the groundwater **changed over time [CCC-7]**. Students observed that the water agents arranged themselves in a specific shape around the entry to the well that Ms. P called a "cone of depression." The water agents were not given instructions to form this pattern, and the surprised students wondered what **caused [CCC-2]** this specific **structure to form [CCC-6]** . Ms. H reiterated the characteristics of complex adaptive **systems [CCC-4]** and described the cone of depression as an emergent pattern. Noticing that each run of the computer model was slightly different led to a discussion of what computer models were good for and how they could help us understand natural and artificial processes (ESS 3.B Human impacts of Earth's systems).

Day 3: Modifying the Base Model and Investigating the Impact of Changing the Evaporation Rate (Explain)

Investigative phenomenon: When the model includes evaporation, the amount of available groundwater changes.

Ms. H asked the students, "How would this model be different if Earth's climate warmed?" She pointed out that "**Computer models [SEP-2]** of global climate predict that California is likely to be warmer and drier on average than at present" and reviewed a piece of critical background knowledge from prior lessons, "The higher the temperature of a substance the greater the kinetic energy of the molecules at its surface and therefore the faster the rate of their evaporation." With these pieces of information in hand, Ms. H led a discussion during which students connected rising local temperatures to evaporation of water droplets. Students then modified the base model to add a new process called "evaporation" and added a slider that controlled the rate of evaporation of water as it fell to Earth.

Students then planned how they would use the model to run an experiment by changing the variable related to evaporation rate. The students **proposed questions [SEP-1]** about the **effect [CCC-2]** of evaporation on ground water pumped to the surface of the Earth. A graphic organizer that Ms. H called an "experimental design form" guided students as they developed scientific questions to investigate using their model. Through scaffolding, the form helped student see the need to use trials and to clearly identify the variables. Students designed and ran their experiment in pairs after specifying which variable they would be changing. Within what range? How many trials at each setting? They used the instrumentation in the model (the graph and the data boxes) to monitor temperature under the different scenarios, students recorded the data from the graph. They then **analyzed [SEP-4]** the results of their experiments, documented the **patterns [CCC-1]** in their findings, and used these as evidence to support a claim **explaining [SEP-6]** one aspect of the system. Ms. H led them to reflect on the real-world implications of their discoveries. Finally, students were asked to think of ways to extend the model, based on what they have learned about California's agriculture, population growth, and water needs.

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Day 4 - Adding Water Pumps to the Model and Running an Experiment (Extend)

Investigative phenomenon: When two wells draw from the same aquifer, the height of the pump head, the distance between the wells, and the amount of pumping all affect whether or not one or both of the wells will run dry.

Ms. H started off the day by reviewing the “Some-for-All-or All-for-One” kinesthetic model that the students ran on day 1. She asked how their water pump model could be used to model a scenario in which many different users were sharing the water resource. After much lively discussion and ideas for changing the model were made, Ms. H suggested that the students keep it simple and start simply by adding a second water pump that pulls from the same aquifer.

Calling on their prior knowledge, Ms. H asked them to review how the first pump was made in code. They described that an agent was used to draw the pump by stamping different colors as they walked. The colored tip of the pump head is used to detect when water molecules hit the head and are pumped out of the ground. Students proceeded to copy and paste the existing “create-pump” procedure to create a new procedure for creating the second pump. Students were able to customize the height of the pump head and the distance of the second pump from the first. Ms. H reminded the students about the engineering cycle and the need to incrementally make changes and test the model frequently.

To respond to student questions in a timely manner and to develop student self-sufficiency as learners while coding, Ms. P employed three tactics. The first was to use pair programming; the second was to use green, yellow, and red cups for signaling status; and the third was to employ an “ask-three-then-me” method of problem solving. In pair programming, one student played the role of the driver, who wrote code while the other, the navigator, made suggestions and reviewed the code as it was typed in. The two programmers switched roles frequently. This practice encouraged communication between the pair and collaborative problem solving. Colored cups were useful to quickly take the temperature of the room. Red cups signaled that the students were stuck and could not move forward, yellow cups signaled that the pair was experiencing difficulty but was trying various solutions; and green cups signaled that all was well with the pair. Since the cups were visible to all, students who were ahead could locate and help pairs that were stuck. Finally, the “ask-three-then-me” tactic encouraged students to ask for suggestions from other students rather than running to the teacher for help. When these three tactics were incorporated into the classroom culture, students learned faster and became more self-sufficient.

HIGH SCHOOL EARTH AND SPACE SCIENCE COMPUTER SCIENCE VIGNETTE APPENDIX 3.3: WATER RESOURCES AND FARMING IN HIGH SCHOOL

Day 5: Testing and Evaluation of Models (Evaluate)

To see if their model was working as expected, students needed to add some instrumentation to determine how much water the aquifer initially held and whether or not it decreased over time. Once students had implemented their code and tested it, students designed an experiment to determine the impact of altering the amount of evaporation rate and/or adding additional water pumps to the system. Using the model as an experimental testbed, students chose to explore parameters and discovered some of the issues and choices that affect water supplies. By the end of the five-day module, students gained a more specific understanding of the processes involved in water availability, storage, and use, and the potential impact of climate change on California's water supply.

After collecting their data, students presented their experiment and **communicated [SEP-8]** their findings, and proposed an **explanation [SEP-6]** for the **data [SEP-4]**. As they presented their findings, they had to account for any unexpected variations and **construct an argument [SEP-7]** about the **cause and effect relationship [CCC-2]** between evaporation and groundwater availability (e.g., the evaporation rate is an important determiner of ground water availability, increases in evaporation rate turn out to be unimportant, or that an unintended variable interferes with the ability to conclude either way).

Days 6–7 (Optional): Computational Science and Engineering Challenge

Investigative problem: How can we reduce the impacts of human activity on the climate?

This optional two-day extension enabled students **to design mitigation strategies [SEP-6]** and then implement and test the strategies using the water-pumping model to determine their potential impact. Students designed their own alterations to the base model consisting of a mitigation strategy, a question, an experimental design, and a model. In the first activity, students isolated and developed their strategy for mitigating water wasting (for example, catching rainwater or implementing scheduled irrigation) considering a range of factors (e.g., crops grown, soil types), and identified the changes they would need to make to their water pump model. This led to a second activity, in which they designed and implemented their model, then used the model as an experimental testbed to assess the impact of their proposed mitigation strategy.

HIGH SCHOOL EARTH AND SPACE SCIENCE COMPUTER SCIENCE VIGNETTE
APPENDIX 3.3: WATER RESOURCES AND FARMING IN HIGH SCHOOL

Vignette Debrief

With computational modeling and simulation, students were able to design investigations to answer "what-if" questions. As they **investigated [SEP-3]** the effects of changing evaporation rate, they were creating computational models that showed how humans alter the interaction between the hydrosphere and atmosphere (HS-ESS3-6). Students could use the results of their models as evidence that helps **explain [SEP-6]** how **changes [CCC-7]** in climate affect water resources, which can therefore alter human activity (HS-ESS3-1).

SEPs. Students performed **investigations [SEP-3]**. They **analyzed their data [SEP-4]** to help understand the relationships between different components in the **system [CCC-4]** they studied. They used these relationships to evaluate **a model [SEP-2]** of the system. They used the data from their investigations along with the reasoning of their model to **construct an explanation [SEP-6]** about the **causes [CCC-2]** of limited groundwater supply. As they made modifications to an existing computer model, students employed engineering practice by **defining the parameters of the problem [SEP-1]** and **designing solutions [SEP-6]**.

DCIs. The competition for water resources is a tangible example of limited natural resources (ESS3.A) and human impacts on Earth systems (ESS3.C).

CCCs. Students applied the crosscutting concept of **systems and system models [CCC-4]** as they thought about the different components and how they interacted. They observed the unique system property/behavior of the cone of depression when they ran the base model for the first time. This feature provided an example in which the **structure [CCC-6]** gives clues about the process that causes it to occur. Students looked for **patterns [CCC-1]** in pumping **data [SEP-4]** to test for **cause and effect [CCC-2]** relationships between number of pumps and captured water, and between evaporation rate and groundwater availability. They learned to question the validity of the **model [SEP-2]** and consider what it could and could not tell us about the real world, an application of CCCs related to nature of science and the interaction between technology and science.

EP&Cs. Water resources support California's vibrant population, its economically vital agricultural sector, and its diverse natural habitats (EP&C I, IV). As such, decisions surrounding these resources are complex and must balance many needs (EP&C V). The kinesthetic model on day 1 provided students a tangible experience about how these decisions are complex. Nonetheless, these decisions are important because humans have the ability to extract groundwater faster than it can be replenished, which can permanently alter the environment (EP&C II, III). The base model does not include the environmental effects of groundwater pumping, but it could be extended to do so. Even without directly modeling interactions with the nonhuman biosphere, students could still notice how humans could affect one another through the multiple-pump experiments on day 4. And the optional extension on days 6–7 provided students the chance to thoroughly brainstorm and test solutions that could minimize these impacts (HS-ESS3-4).

HIGH SCHOOL EARTH AND SPACE SCIENCE COMPUTER SCIENCE VIGNETTE APPENDIX 3.3: WATER RESOURCES AND FARMING IN HIGH SCHOOL

CA CCSS Connections to English Language Arts and Mathematics. Throughout the vignette, students participated in several small-group and whole-class discussions (SL.9–12.1a–d, 4, 5). Students participated in a computer simulation, which involved a base model of a water pump. Students added a variable of evaporation to see how it impacted the amount of water pumped. Students then added a second water pump that pulled from the same aquifer; this was done to simulated different users drawing from the same water supply. Students argued (WHST.9–12.1) one of these three hypotheses: the evaporation rate was an important determiner of ground water availability; increases in evaporation rate were unimportant; or an unintended variable interfered with the ability to conclude either way (S-IC.1, 2, 5, 6).

Resources

Several of the activities described in this vignette were adapted from other sources and are cited within. Please refer to them for more detail.

The Project GUTS Introduction to Computer Modeling and Simulation module is available at https://www.cde.ca.gov/ci/sc/cf/appx3.asp#link18.

The Project GUTS Water Resources module is available at https://www.cde.ca.gov/ci/sc/cf/appx3.asp#link19.

High School Physics Vignette: Electrical Forces

HIGH SCHOOL PHYSICS COMPUTER SCIENCE VIGNETTE APPENDIX 3.4: ELECTRIC FORCE INQUIRY INVESTIGATION IN HIGH SCHOOL

Written by Dean Reese

Performance Expectations

Students who demonstrate understanding can do the following:

HS-PS2-4. Use mathematical representations of Newton's Law of Gravitation and Coulomb's Law to describe and predict the gravitational and electrostatic forces between objects. [Clarification Statement: Emphasis is on both quantitative and conceptual descriptions of gravitational and electric fields.] [*Assessment Boundary: Assessment is limited to systems with two objects.*]

Highlighted Science and Engineering Practices	Highlighted Disciplinary Core Ideas	Highlighted Crosscutting Concepts
[SEP-5] Using Mathematics and Computational Thinking	PS2.B Types of Interactions	[CCC-1] Patterns

CA CCSS Math Connections: MP.2, MP.4, HSN-Q.A.2, HSA-SSE.A.1

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

CA CCSS for ELA/Literacy Connections: RST.11–12.1, RST.11–12.7, WHST.9–12.9

Introduction

Students investigate the factors relevant to the Electric Force (Coulomb's Law) by exploring static electricity phenomena and by building a computer simulation in order to understand.

Length and position in course. This vignette represents about two weeks of instruction that comes at the beginning of an instructional segment on Coulomb's law. It is assumed that students had limited prior knowledge about electrical interactions. Because students develop the equation of Coulomb's law using an inquiry approach, this vignette needs to come before students read any textbook material on the subject.

Prior knowledge. Students need to be familiar with the internal structure of atoms and know about the charged particles within the atoms.

This vignette assumes that students have completed a multi-day sequence introducing computer modeling and simulation (such as module 1 of the Code.org CS in Science curriculum). Students need basic skills in reading and modifying computer codes. They need to interpret an existing base model and make modifications to it by adding new codes or altering the ones that exist. While this vignette provides opportunities to practice those skills, they are not specifically addressed in this lesson outline.

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

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Day 1: The Mystery of the Transparent Tape (Engage)

Students investigate several situations where objects are attracted to one another.

Days 2–3: Qualitative and Quantitative Models (Explore/Explain)

Students investigate additional static electricity phenomena in a hands-on lab and then use a computer visualization to develop qualitative models that explain the phenomena. They then create quantitative models of these attractions by coding computer simulations.

Days 4–5: Lab Stations to Refine the Mathematical Model (Explore/Explain)

Students rotate through lab stations where they directly investigate electrostatic forces or obtain information about them. They refine their models in groups and then spend an entire day in a whole-class science-talk discussion to determine the equation of Coulomb's law.

Day 6: Applying Coulomb's Law (Elaborate)

Students apply Coulomb's law to a variety of circumstances.

Day 7: Coding Coulomb's Law (Elaborate)

Students compare their paper-and-pencil calculations to their code from day 3 and then modify the code to accurately reflect Coulomb's law.

Day 8 (Evaluate): Computational Science & Engineering Challenge

Students complete an assessment where they cite evidence and reasoning to support Coulomb's law, comment sample code, and apply Coulomb's law to several scenarios.

Day 1: The Mystery of the Transparent Tape (Engage)

Anchoring phenomenon: When two pieces of transparent tape are pulled apart, they interact with one another.

Mr. R handed out two pieces of transparent tape to each student in class. Then he showed the students how to stick one piece of tape to another piece of tape, and then how to pull them apart (https://www.cde.ca.gov/ci/sc/cf/appx3.asp#link20). One piece of tape became positively charged and the other became negatively charged. Mr. R then asked students to think/pair/share on what they think happened to cause the two pieces of tape to interact in this way. Mr. R was mindful that at this stage of the lesson it was important to simply listen to the student's answers as opposed to qualifying them as right or wrong.

Each student pulled the two pieces of tape apart and experienced the electric force interaction that occurred between the two. Students were usually baffled by the interaction and had not expected to see this result. Students were asked to think about what was happening and to discuss with a partner next to them in class about why the phenomenon that they saw occurred. Then students were randomly called on to share their partner's thoughts on the situation.

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Mr. R introduced the Van de Graaff generator, highlighted some of the different parts, and then demonstrated the generator discharging to a grounding rod. Mr. R asked students to identify what the two demonstrations had in common. Students noted that both involved something pushing or rubbing together. Mr. R notes that they would return to this observation as they explained the next phenomenon.

Explore/Explain

Investigative phenomenon: Pie tins placed on top of a Van de Graaf generator seem to fly away as the generator is turned on.

The idea of placing 10 aluminum pie tins on top of the Van de Graaff generator and turning it on was presented to the students but not carried out at that point. Before conducting the pie-tin demonstration, Mr. R asked students to write a paragraph predicting what they thought would occur when he turned the generator on with the pie tins on top and why. Students were encouraged to draw the system and add annotations to the drawing to help develop their thinking. Mr. R asked the students to share their thinking with the students around them and then had students share their expectations about what would happen.

Then Mr. R commenced the pie-tin demonstration. Pie tins were pushed apart one by one and fell off the generator. After the demonstration, the class discussed what they actually saw and possible explanations of how it had happened. Mr. R asked students to circle places in their original drawing that they think are accurate and put boxes around sections that they would like to now change. Students wrote a paragraph explaining what actually occurred in the demonstration and the reasoning behind why it may have occurred. Mr. R emphasized the importance of using their actual observations as evidence in this preliminary **explanation [SEP-6]**.

Day 2: Qualitative and Quantitative Models (Explore/Explain)

Investigative phenomenon: A balloon sticks to the wall after being rubbed back and forth across a student's hair.

Mr. R engaged students this day with a few quick static electricity demos, including making a balloon stick to the wall and having a student feel a shock when reaching out to touch a metal doorknob after having rubbed her feet across the carpet. He asked students to identify similarities between these two phenomena and the previous day's phenomena. He then instructed students to explore two simulations of these phenomena from PhET, John Travoltage (https://www.cde.ca.gov/ci/sc/cf/appx3.asp#link21) and the Balloons and Static Electricity (https://www.cde.ca.gov/ci/sc/cf/appx3.asp#link22). They recorded observations of how objects become charged and the resulting forces from this buildup of charge.

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Students then revisited their models and explanations from the previous day. After having had them discuss in pairs and as a class, he had students individually redraw their diagrams using their new understanding of how electric charges work.

Elaborate

At this point, students had developed a qualitative **model [SEP-2]** of electrical charges attracting and repelling one another. The qualitative model does a good job of describing the general **cause and effect relationships [CCC-2]** they have observed, but it does not help them predict the strength of the electrical forces. Scientists always strive to **quantify [CCC-3]** the electric force so they can make more meaningful predictions. Mr. R told students that they would use the simulation software NetLogo to turn their qualitative models into quantitative ones. Mr. R modeled how to incorporate mathematical equations into a NetLogo simulation using an energy conservation model that the students had used previously in class (see https://www.cde.ca.gov/ci/sc/cf/appx3.asp#link23). Then Mr. R asked students to list the factors that they thought might affect the strength of the electric force. Students had **asked questions [SEP-1]** about these factors during the middle grades, MS-PS2-3. In this exercise, students worked in teams to combine the factors that determine the electric force into a possible equation for the electric force. Students were not allowed to use the book or Internet resources; only their insights from the previously observed phenomena were used to shape these mathematical models. Different teams had come up with very different equations, and few of them resembled the commonly accepted scientific equation at this point.

Students examined code from a simulation that incorporated mathematical equations into NetLogo. Mr. R assigned different groups to explain different sections of the code to the rest of the class. He circulated around to make sure that each group had properly traced through their code. One new coding tool that the example demonstrated was the idea of a global variable. Mr. R called on students to identify where the variable was used in their section of the code.

Mr. R then asked students to create a NetLogo simulation of the electric force interaction of two charges. To make this simulation, they modified code from a base model they had previously worked with. As students worked, Mr. R asked them to rotate who was the "pilot" and who were the "co-pilots" every 15 minutes throughout the coding portion of lesson. Some students coded systems in which the charges were stationary and others coded simulations that were dynamic, meaning that one or both of the charges moved as a result of the electric force. They embedded their mathematical model for the electric force into their simulations using global variables in their code.

Day 3: Finish Coding (Explain, continued)

Mr. R asked several students to briefly present the unfinished program that they had been building. He chose groups that either had interesting code development or had an interesting mental model of the factors that contribute to the electric force. The aim was to share the various mathematical forms of the electric force as well as how students had gone about incorporating the equations into their simulations.

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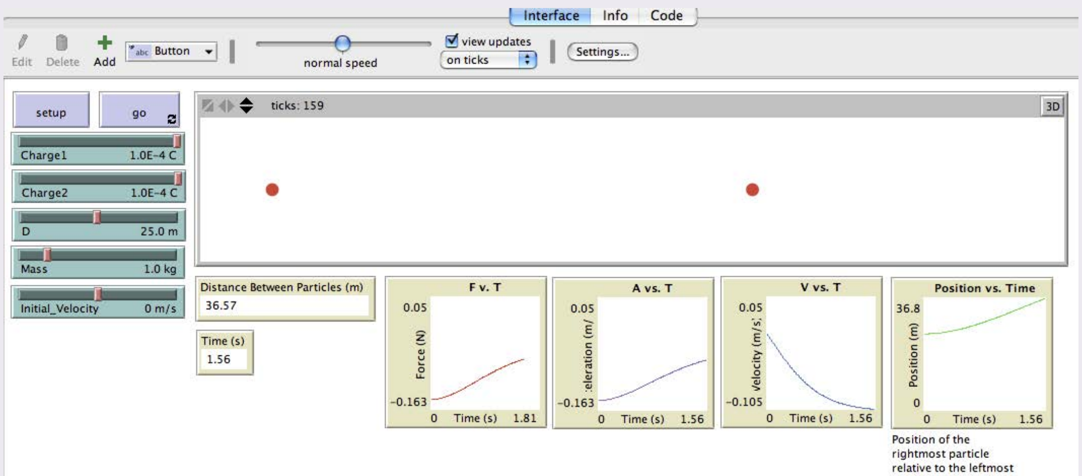
Students continued coding their electric force simulations and were reminded to rotate who was the "pilot" of the simulation throughout the class period. Students submitted the code—finished or unfinished—to Edmodo by the end of the class period. Figure app 3.2 shows an example of student work.

Figure App 3.2. Student Example of a NetLogo Simulation of Electric Force

Entire Simulation created by four students in group A



Source: Wilensky 1999
Long description of Figure App 3.2.

Information Tab:

What is it?
This model is used to quantitatively simulate the interactions between two particles with the electric force (F). The simulation uses initial conditions and Coulomb's Equation for the electric force in order to model particle–particle interaction.

How it works:
This model uses multiple equations in order to function. The bases of these equations are dictated by the globals defined within the code and in the user interface (UI):

- [charge1] and [charge2] are globals defined in the UI; they correspond to the given charge (in Coulombs). Charge1 defines the left particle's charge, and Charge 2 defines the right particle's charge. The color (via the globals [color1] and [color2]) of each particle also corresponds to its charge, with neutral displaying gray, negative displaying black, and positive displaying red.
- [D] is a UI-defined global that represents distance.

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- [Mass] is defined in the UI and is uniform between the two particles.
- [Initial_Velocity] is the beginning velocity of the rightmost particle.
- [F] is defined as the electric force and is defined by Coulomb's Equation embedded into the code: F = k(charge1)(charge2)/(D ^ 2)
- [A] is defined as the acceleration of the rightmost particle, defined by Newton's Second Law, embedded in the code: F = mA and A = F/m
- [V] is the given velocity of the rightmost particle, defined as a function of time and acceleration: V = (initial_velocity) + (A * T)
- [X] is the position of the rightmost particle. It changes depending on the velocity defined above.
- [T] represents time, as a replacement of ticks. Within the code, the value for T increases by 0.01 every 0.01 seconds. As such, T represents time in the real world.
- [R] is the distance between two particles, which is identical to X.
- [k] is Coulomb's constant, defined as 9 * (10 ^ 9) at the setup phase of the code.

How to Use It:

(1) Select values for the particle's charges and the distance between them. Choose values for their mass and the rightmost particle's initial velocity. (2) Hit the setup button. (3) Hit the go button to begin the simulation. At any point during the model, the go button can be deselected to stop the model manually.

Things to Notice:

As the simulation is running, notice the velocity of the right particles. Is it constant or does it change? How does the movement of the particle relate to its distance from the left particle?

Things to Try:

(1) Make one or both charges neutral. What happens? (2) If both charges are positive, do the particles repel or attract? (3) How does the mass affect velocity? Try increasing the mass and using the graph provided to examine this relationship.

Extending the Model:

This is a simplistic model of the electric force, in which only one particle moves at a time. To extend this model, both particles can be allowed to move. In addition, more than two particles can be included in the model to demonstrate the addition of force vectors.

NetLogo Features:

Note the use of [globals] at the top of the code to define variables not present in the user interface. The most important part of this model is provided by the relationships defined by equations embedded in the simulation. View the "How-it-Works" section to see more.

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Related Models:
This model is most like the "Traffic Basic" model in the NetLogo Model Library. It uses a similar interaction between acceleration, velocity, and position for the right particle.

Credits and References:
Programmed by Joshua Abraham, Joe Garcia, Ryan Wang, and Jace Marcos

Teacher: Mr. Reese, Tracy High School, IB Physics Period 1

Day 4: Lab Stations to Refine the Mathematical Model (Explore)

Investigative phenomenon: Sometimes two charged objects attract one another and sometimes they repel. Two objects repel one another more when they are close together or when more rubbing is done to charge them.

Mr. R set up four stations for the students to cycle through. Station 1 had one ring stand with a polystyrene insulator hanging from it by a cotton string and a second ring stand with a crumpled ball of aluminum foil hanging from it by a cotton string. This station also had a fur pelt, glass rod, plastic rod, silk, balloons, and a metal rod. Station 2 had a close reading that focused on the details of the electric force without stating the equation explicitly (figure app 3.3). Station 3 had a computer simulation (https://www.cde.ca.gov/ci/sc/cf/appx3.asp#link26) that allowed students to generate simulated distance and force data between two charges. Station 4 had another close reading focused on how electric forces translate into accelerations of the charged object (figure app 3.4).

At each station students documented what they saw, wrote questions that arose, and collected data where appropriate. At the stations where they obtained information [SEP-8] from articles, they highlighted quotes from the reading that would provide evidence for their claim regarding factors that affect the electric force.

Explain

After students had spent about 10 minutes each at the four stations, Mr. R asked the students to revisit their equations of magnetic force. He asked them to prepare comments for the next day's whole class discussion on the topic of factors that affect the electric force. Students reflected and wrote about how the experience of the four stations had affected their thinking regarding the factors that affect the electric force. This reflection went into their lab notebooks.

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Day 5: Explaining the Lab Stations (Explain)

Mr. R set up the ground rules for the day's discussion topic: "What factors affect the electric force?" He asked the students to take five minutes to review all data collected, important text from the close reading articles, and observations from station 1 that may be relevant to answering the question. He also explained to the students that their participation would go toward the class participation grade. During the whole class discussion, Mr. R purposefully removed himself from the discussion and let the class know that he would just be an observer. He did not try to qualify the answers from the group during this discussion, as this would have interfered with the students' discourse. However, when things veered off topic, he reminded students of the discussion focus.

After the discussion Mr. R revealed Coulomb's law to the class by writing it on the white board. He showed a short YouTube video that illustrated Coulomb's torsion balance experiment (https://www.cde.ca.gov/ci/sc/cf/appx3.asp#link27). He asked students to write an entry in their lab notebook comparing their group's equation to Coulomb's law. He also asked them to consider the following questions: What did they have in common and what was different? Did they have the same terms? Did their equation follow a similar form or structure? What information did Coulomb have that they did not?

Day 6: Applying Coulomb's Law (Elaborate)

After students had seen the form of Coulomb's law, they applied it to predict the force between charges in different circumstances. The students first worked independently, applying Coulomb's Law to the various situations presented in the problem set. When students were struggling on a particular problem, they spent a few minutes trying to figure it out and then moved on to the next problem. After 30 minutes they moved to their lab groups to discuss the solutions with their peers and with the support of Mr. R.

Days 7: Coding Coulomb's Law (Elaborate)

Students revisited their code from day 3. Mr. R selected a few of the word problems from day 6 and asked the students to determine if their original code would provide the correct answer, predict a smaller force, or predict a larger force than they calculated using Coulomb's law. He then asked them to modify their old code so that it reproduced the scenario in the word problem and to see if they had accurately predicted their model's behavior. Then, he had them modify the code so that it included the correct version of Coulomb's law. And he asked them, "Did the code produce the same answer as their manual calculations?" Mr. R then introduced a third problem that was very complex and difficult to complete by hand. Students used their code to solve this problem.

Day 8: Evaluate

Mr. R gave students an assessment on the objectives for the learning sequence. The individual written assessment involved three parts. The first part required students to support claims, with appropriate evidence and reasoning, about different factors that affected the

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electric force. The second part of the assessment required students to comment lines of code from one of the student models of the NetLogo electric force simulations. The third part of the assessment required students to apply Coulomb's Law to various situations to solve for the electric force.

Vignette Debrief

This vignette presented an innovative approach to teaching one of the classic equations in physics. Rather than give students Coulomb's law and have them simply apply it, Mr. R provided students a range of phenomena to investigate electrostatic interactions. He had them develop a qualitative model on day 2, which they then extended into a quantitative model. Mr. R had students code up their mathematical representation, even though most of the students had a scientifically incorrect equation. He did this intentionally so that students could return to their model and revise it after they had additional information. After these rich experiences, students were much more familiar with Coulomb's law and could apply it to predict electrostatic forces between objects (HS-PS2-4).

SEPs. Students developed qualitative and quantitative **models [SEP-2]** of electrostatic interactions, refined their model, and then applied it to predict behavior in a range of circumstances. As students struggled to formulate an equation for the strength of the electrostatic force, they employed **mathematical thinking [SEP-5]**. They then used **computational thinking [SEP-5]** to convert the mathematics into a computer code. The science talk session on day 5 required students to **engage in argument from evidence [SEP-7]**, which eventually allowed students to construct meaningful **explanations [SEP-6]** of the factors that **influence [CCC-2]** electrostatic forces during the assessment on day 8.

DCIs. Students developed an in-depth understanding of the factors that influenced electrostatic forces, one form of interaction (PS2.B).

CCCs. Through repeated exposure to related phenomena, students identified **patterns [CCC-1]** about how objects became electrically charged and the factors that influenced the electrostatic forces between them. Students' initial mathematical model of electrostatic interactions often incorporated several of the correct **causal mechanisms [CCC-2]**, but few students correctly identified the inverse square **proportional [CCC-3]** relationship without additional information. While simply listing the factors may have been sufficient in earlier grades, the high school level of understanding of **cause-and-effect [CCC-2]** for Coulomb's law required that students quantify the relative importance of the different factors.

EP&Cs. Much like Coulomb's law described the interactions between the two pieces of transparent tape on day 1, it also described adhesion of contaminants to soil in groundwater. Mr. R could have extended the lesson to show different ways that electrostatic interactions are used in real-world engineering solutions such as water filtration.

CA CCSS Connections to English Language Arts and Mathematics. Throughout the vignette, students participated in several small-group and whole-class discussions (SL.6–8.1a–d, 4, 5). They gathered information from several sources (RST.6–8.3, 9) to make

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scientific arguments supported by evidence (WHST.6–8.1). Coding was an excellent example of reasoning quantitatively (MP.2) and modeling using mathematics (MP.4). Teachers could emphasize different aspects of the Coulomb's law equation to connect to CA CCSS Mathematics concepts at the appropriate level of complexity for their students. Students could have recognized the structure of the equation as a multi-variable equation with terms and coefficients (A-SSE.1). Teachers could have prompted students to graph and interpret the function from different representations (F-IF.7), identify the key features of the function (F-IF.4), and explicitly discuss the domain over which it is valid in the real world (F-IF.5). By graphing Coulomb's law for a certain pair of charges at different distances apart, students could have noticed that the rate of change of the function is large when the charges are close together but is small when the particles move farther apart. Students could have asked questions about how this behavior related to the structure of the equation they wrote (F-IF.6).

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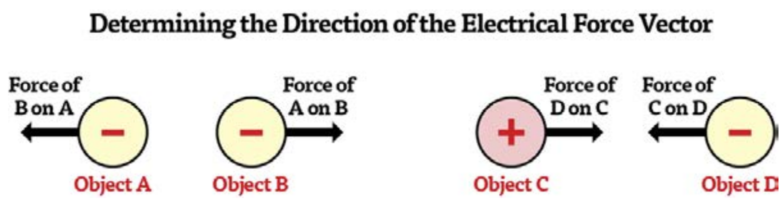
Figure App 3.3: Student Handout: The Electric Force Close Reading #1

Directions: Read this article (https://www.cde.ca.gov/ci/sc/cf/appx3.asp#link28) specifically for any information that will help you understand the factors that affect the electric force. You are looking for evidence and reasoning that will support your claim. Highlight all relevant information with regard to this focus.

Force as a Vector Quantity

The electrical force, like all forces, is typically expressed using the unit Newton. Being a force, the strength of the electrical interaction is a vector quantity (https://www.cde.ca.gov/ci/sc/cf/appx3.asp#link29) that has both magnitude and direction. The direction of the electrical force is dependent upon whether the charged objects are charged with like charge or opposite charge and upon their spatial orientation. By knowing the type of charge on the two objects, the direction of the force on either one of them can be determined with a little reasoning. In the diagram below, objects A and B have like charge causing them to repel each other. Thus, the force on object A is directed leftward (away from B) and the force on object B is directed rightward (away from A). On the other hand, objects C and D have opposite charge causing them to attract each other. Thus, the force on object C is directed rightward (toward object D) and the force on object D is directed leftward (toward object C). When it comes to the electrical force vector, perhaps the best way to determine the direction of it is to apply the fundamental rules of charge interaction (opposites attract and likes repel) using a little reasoning.



Long description of Figure App 3.3.

Electrical force also has a magnitude or strength. Like most types of forces, there are a variety of factors that influence the magnitude of the electrical force. Two like-charged balloons will repel each other and the strength of their repulsive force can be altered by changing three variables. First, the quantity of charge on one of the balloons will affect the strength of the repulsive force. The more charged a balloon is, the greater the repulsive force. Second, the quantity of charge on the second balloon affects the strength of the repulsive force. Gently rub two balloons with animal fur, and they repel a little. Rub the two balloons vigorously to impart more charge to both of them, and they repel a lot. Finally, the distance between the two balloons has a significant and noticeable effect upon the repulsive force. The electrical force is strongest when the balloons are closest together. Decreasing the separation distance increases the force. The magnitude of the force and the distance between the two balloons is said to be *inversely related.*

HIGH SCHOOL PHYSICS COMPUTER SCIENCE VIGNETTE APPENDIX 3.4: ELECTRIC FORCE INQUIRY INVESTIGATION IN HIGH SCHOOL

Figure App 3.4: Student Handout: The Electric Force Close Reading #2

Directions: Read this article (http://www.cde.ca.gov/ci/sc/cf/appx3.asp#link30) specifically for any information that will help you understand the factors that affect the electric force. You are looking for evidence and reasoning that will support your claim. Highlight all relevant information with regard to this focus.

The attractive or repulsive interaction between any two charged objects is an electric force. Like any force, its effect upon objects is described by Newton's Laws of Motion. The electric force—F_{elect}—joins the long list of forces that can act upon objects. Newton's laws are applied to analyze the motion (or lack of motion) of objects under the influence of one force or combination of forces. The analysis usually begins with the construction of a free-body diagram in which the type and direction of the individual forces are represented by vector arrows and labeled according to type. The magnitudes of the forces are then added as vectors in order to determine the resultant sum, also known as the net force. The net force can then be used to determine the acceleration of the object.

In some instances, the goal of the analysis is not to determine the acceleration of the object. Instead, the free-body diagram is used to determine the spatial separation or charge of two objects that are at static equilibrium. In this case, the free-body diagram is combined with an understanding of vector principles in order to determine some unknown quantity in the midst of a puzzle involving geometry, trigonometry, and Coulomb's law. In this last section of Lesson 3, we will explore both types of applications of Newton's laws to static electricity phenomenon.

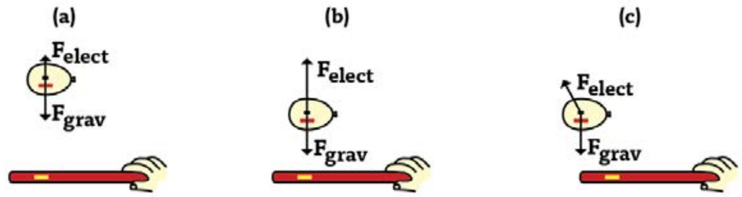
Electric Force and Acceleration

Suppose that a rubber balloon and a plastic golf tube are both charged negatively by rubbing them with animal fur. Suppose that the balloon is tossed up into the air and the golf tube is held beneath it in an effort to *levitate* the balloon in midair. This goal would be accomplished when the spatial separation between charged objects is adjusted such that the downward gravity force (F_{grav}) and the upward electric force (F_{elect}) are balanced. This would present a difficult task of manipulation as the balloon would constantly move from side to side and up and down under the influences of both the gravity force and the electric force. When the golf tube is held too far below the balloon, the balloon would fall and accelerate downward. This would in turn decrease the separation distance and lead to an increase in the electric force. As the F_{elect} increases, it would likely exceed the F_{grav} and the balloon would suddenly accelerate upward. And finally, if the *point of charge* on the golf tube is not directly under the *point of charge* of the balloon (a likely scenario), the electric force would be exerted at an angle to the vertical and the balloon would have a sideways acceleration. The likely result of such an effort to levitate the balloon would be a variety of instantaneous accelerations in a variety of directions.

HIGH SCHOOL PHYSICS COMPUTER SCIENCE VIGNETTE APPENDIX 3.4: ELECTRIC FORCE INQUIRY INVESTIGATION IN HIGH SCHOOL

Figure App 3.4: Student Handout: The Electric Force Close Reading #2 *(continued)*

Levitating a Balloon



(a) When the charged tube is held too far from the charged balloon, the repulsion force is less; the acceleration of the balloon is downward. (b) When the charged tube is held too close to the charged balloon, the repulsion force is greater; the acceleration of the balloon is upward. (c) When the charged tube is not directly beneath the charged balloon, there is a sideways acceleration.

Long description of Figure App 3.4.

References

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