Chapter 11

Instructional Strategies for CA NGSS Teaching and Learning in the Twenty-First Century

2016 Science Framework

FOR CALIFORNIA PUBLIC SCHOOLS
Kindergarten Through Grade Twelve

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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.

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CHAPTER 11

Instructional Strategies for the Next Generation Science Standards for California Public Schools, Kindergarten Through Grade 12 Teaching and Learning in the Twenty-First Century

Introduction

The California Next Generation Science Standards (CA NGSS) shift expectations from simply knowing about science to being able to engage in rich science experiences. Teachers must support that shift with the tools and techniques they use in their classrooms. This chapter illustrates strategies that align with the three-dimensional learning goals of the CA NGSS and prompts teachers to reflect on successful elements of their own teaching so that they can make informed choices about which strategies to employ in their own classrooms. Instructional strategies operate at many levels in an educational experience. An instructional strategy is a teaching method that activates students' curiosity about a topic and engages students in learning. It helps them develop their critical thinking skills, keeps them on task, and engenders purposeful and sustained classroom interaction. In general, an effective instructional strategy should enable and enhance students' learning of course content.

This chapter outlines research-based strategies that operate at a range of scales including broad frameworks for thinking about science learning, principles of curriculum design, tools for lesson planning, and minute-by-minute instructional techniques. These tools should be integrated with the classroom assessment strategies in chapter nine.

Key Instructional Shifts—Student-Centered Learning Environments

Chapter one of this framework describes three essential elements of CA NGSS instruction that were not given explicit emphasis in California's previous science standards. The CA NGSS are

- *three-dimensional*—students engage in scientific inquiry of phenomena using all three dimensions of NGSS;
- *coherent across the curriculum*—learning builds upon itself from year to year, and science integrates with other parts of the curriculum; and
- *relevant to local communities and student interests*—content and practices build on students' existing experience to learn about and solve real-world societal and environmental problems.

Students benefit the most from these elements when their ideas and questions are at the center of instruction. It is the teacher's role to provide the context and the support to develop, modify, and use student ideas. To make instruction more three dimensional, students must engage in the **science and engineering practices (SEPs)** themselves, internalize the **disciplinary core ideas (DCIs)** so that they can link them with their existing knowledge, and use the **crosscutting concepts (CCCs)** as templates for their own thinking. Making the curriculum more coherent requires that students themselves draw explicit connections between ideas they are learning. Engaging students in relevant issues requires connecting to students' everyday experiences. Student-centered learning environments extend beyond the classroom to the schoolyard, the community, parks, outdoor schools, museums, zoos, aquariums, virtual platforms, and beyond. Throughout this framework, when we refer to learning environments, we are referring to student-centered learning spaces both in the classroom and in the field. Table 11.1 identifies instructional shifts reflective of student-centered learning environments. These environments include shifts in teacher and student activities, both of which are accomplished by deliberate instructional choices.

Table 11.1. Instructional Shifts Required by the CA NGSS

More of this...	Less of this...
Students engage in the CA NGSS practices to build a deeper understanding of science and engineering content and make sense of phenomena and design solutions.	Students study the meaning of science content that teachers explain to them. Students memorize definitions and rote procedures.
Students develop models of systems within the natural world and use them to explain phenomena or solve problems.	Teachers present models that describe phenomena in the natural world.
Students learn science as an iterative, dynamic, creative, and collaborative process similar to how real scientists and engineers do their work.	Students learn science as a collection of facts and learn that these facts were found using a singular and linear "scientific method," disconnected from how real scientists and engineers do their work.
Practices provide students with relevant, real-world learning in which they must investigate and problem solve using critical thinking.	Students learn to conduct investigations following step-by-step instructions.
Students build science and engineering understanding using a variety of practices in investigations, experiments, and project-based experiences.	Students use one practice per investigation/experiment.

Table 11.1. Instructional Shifts Required by the CA NGSS *(continued)*

More of this...	Less of this...
Science content and science practice are integrated.	Science content and practices taught in isolation.
Student reasoning and argumentation play a central role in understanding labs and text.	Student thinking is limited by a “cook-book” approach to lab experiences and problems or end-of-the-chapter questions and test experiences.
Science and engineering notebooks reflect student thinking using the science and engineering practices to understand content and show development and revision of students’ scientific models.	Science notebooks reflect only students’ ability to take notes or copy teacher models.
Engineering is integrated into all science disciplines.	Engineering is treated as an add-on.
Engaging in science and engineering practices allows students to revise their thinking and understanding.	The science process is just a thing to learn/ apply and “be done.”
Students are actively engaged in the practices through investigations and experiments and technologies they have generated.	Students are passively engaged in watching or participating in teacher-directed investigations and experiments.
Crosscutting concepts build a deeper and more connected understanding of science as a whole.	No connection among science content.
Connection of the practices to the goals of literacy in science (purposeful reading and writing to strengthen science understanding).	Reading and writing disconnected from the purpose of learning.
Student-to-student discourse is productive, using practices to explain phenomenon or solve problems.	Student-to-student discourse is limited due to activities that provide only one exact outcome.
Teacher questioning prompts and facilitates students’ discourse and thinking.	Teacher questions students to seek a confirmatory right answer.
Learning takes place routinely in a variety of settings: in the classroom, outdoors, in school gardens and in the field, in museums and aquariums, and in the community.	Learning only occurs indoors in the classroom.

How People Learn Should Guide All Instructional Strategies

The key principles of the CA NGSS are not arbitrary—they reflect decades of research on how people learn. The most effective instructional strategies also capitalize on these findings. National Research Council (NRC) (2007b) identifies four guiding principles about how students learn science:

- *Students are more likely to understand and use ideas when they have had concrete and relevant experiences to draw upon.* When students have prior experience with a phenomenon, they can more easily connect new ideas to their existing knowledge structure. For example, students who grow up in the Southern California desert will be familiar with the feeling of sand blasting against their face during a gust of wind, helping them develop a conceptual model of wind erosion more quickly than student who grow up in Northern California, where moist soil covered by vegetation rarely blows away. The fact that students from enriched backgrounds have such a diversity of out-of-school experiences may be one reason (but not the only reason) that they often perform better in school than their peers. Providing students common exploratory and open-ended classroom and field-based experiences allows teachers to assess students' prior knowledge and provides opportunities to address potential gaps in student knowledge or experience.
- *Students come to school with preexisting ideas about how the world works.* They may not be familiar with the specialized language of science or accepted abstract scientific models, but they certainly have thoughts about how the world works. Asking a four-year-old why it rains gives insight into the child's unique and creative ideas, and research shows that many people carry similar ideas into adulthood. The most effective strategies to change these preconceptions require several steps: (1) students must recognize and articulate their ideas and preconceptions; (2) students must recognize their ideas fail to explain what they actually observe; and (3) students must discover an alternative idea that works better.
- *Learning is an active process.* Think of knowledge acquisition as a game of Tetris where students must deliberately manipulate and position new ideas rather than a rainstorm with a flood of knowledge pouring from the sky into the ocean below. People cannot simply "absorb" new information—they must actively take external information and integrate it into their own internal knowledge structures. They must figure out how to reconcile new ideas with prior experiences, preconceived ideas, and prior science learning. Instructional strategies should help students make connections between and among the ideas and provide them the time to make these valuable connections.

- *Learning is maximized when students actively apply new ideas after being introduced to them.* The age-old adage of "use it or lose it" applies to learning as the brain forges neural pathways to the most vital, frequently used ideas and prunes out those that are unused. Having students apply ideas to new contexts forces students to revisit their mental models, revise them, and then connect them to other ideas rather than just retaining the ideas as isolated facts that are less likely to endure. Engineering design challenges are one of many ways that students can apply ideas to new contexts.

Depth of Knowledge and the CA NGSS

One way to conceptualize the shifts embedded within the CA NGSS is to describe the level of cognitive engagement and complexity required of students. Deeper learning, defined as the process through which a student becomes capable of taking what was learned in one context and applying it to new situations (NRC 2010), requires exposing students to a deeper level of intellectual challenge and engagement. The tasks that students are asked to do, whether in the classroom, for homework, or for assessment purposes, all contribute to the level of learning they are likely to achieve. Since one goal of the CA NGSS is that students can apply science understanding to problems that they encounter as future citizens, students must perform tasks in school where they practice applying their knowledge.

Several conceptual frameworks exist for describing the complexity of cognitive tasks, including the revised Bloom's Taxonomy (remembering, understanding, applying, analyzing, evaluating, and creating) and Webb's Depth of Knowledge (DOK) (Webb 1997). Matrices even exist to relate these schemes (Hess et al. 2009). These organizational schemes are useful for gauging the range and balance of intellectual challenge presented to students. The DOK comprises four levels of cognitive demand, as illustrated in table 11.2. In order to reach a desired knowledge level, teachers must employ activities that reach that level.

The CA NGSS performance expectations require students to engage in activities at DOK levels 3 and 4. For this reason, CA NGSS instruction should aim at using levels 1 and 2 only as a foundation to achieve higher DOK levels and never as a final instructional goal. As educators analyze the cognitive demands and complexity associated with specific student tasks, they can use the DOK levels to adapt a task and sequences of tasks to promote deeper understanding.

Table 11.2. Examples for Each DOK Level in Science

Level 1 - Recall and Reproduction

Knowledge necessary to answer an item automatically provides the answer.

- Recall or recognize a fact, term, definition, one-step procedure, or property
- Demonstrate a rote response
- Use a well-known formula
- Represent in words or diagrams a scientific concept or relationship
- Provide, label, or recognize a standard scientific representation or model for a simple phenomenon
- Perform a routine procedure, simple science process, or set procedure (recipe)
- Identify, calculate, or measure

Level 2 - Skills and Concepts

Knowledge necessary to answer an item does NOT automatically provide the answer. Multiple steps.

- Specify and explain the relationship between facts, terms, properties, or variables
- Describe and explain examples and nonexamples of science concepts
- Select a procedure according to specified criteria and perform it
- Collect, organize, represent, and compare data
- Make a decision as to how to approach the problem
- Classify, organize, or estimate
- Make observations
- Interpret information from a simple graph

Level 3 - Strategic Thinking

More than one response possible, calls for use of reasoning, justification, and evidence.

- Interpret information from a complex graph
- Use reasoning, planning, and evidence
- Develop a model to describe a system and the relationships between elements of the system
- Explain thinking (beyond a simple explanation or using only a word or two to respond)
- Justify a response
- Identify research questions and design investigations for a scientific problem
- Use concepts to solve nonroutine problems with more than one possible answer
- Develop a model for a complex situation
- Form conclusions from experimental or observational data
- Complete a multi-step problem that involves planning and reasoning
- Provide an explanation of a principle
- Cite evidence and develop a logical argument
- Conduct a designed investigation
- Research or explain a scientific concept

Table 11.2. Examples for Each DOK Level in Science *(continued)*

Level 4 - Extended Thinking Often requires an extended period of time; however, time alone is not a distinguishing factor.
• Select or devise approach among many alternatives to solve a problem • Deduce the fundamental relationship between several controlled variables using data provided by a complex experiment that is novel to the student • Analyze whether a model can explain relevant aspects of a phenomenon and revise it accordingly • Conduct an investigation, from specifying a problem to designing and carrying out an experiment, to analyzing its data and forming conclusions • Relate ideas within the content area or between content areas • Develop generalizations of the results obtained and the strategies used and apply them to new problem situations

Source: Hess 2010

From Science as Learning Facts to Science as Explaining Phenomena

In CA NGSS classrooms, students should use evidence to explain observable phenomena and justify the solution to problems. How can teachers make this happen? An approach called “Ambitious Science Teaching” (https://www.cde.ca.gov/ci/sc/cf/ch11.asp#link1) distills more than a decade of research about how teachers can structure their instruction around phenomena (Sandoval 2003; NRC 2005 and 2007b; Schwarz and White 2005; Windschitl, Thompson, and Braaten 2008 and 2011; Windschitl et al. 2012). Ambitious Science Teaching identifies four key instructional practices that align closely with the three dimensions of CA NGSS:

1. Select big science ideas that are embedded in observable phenomena.
2. Elicit students’ current thinking and ideas so that they can be used as resources for subsequent learning.
3. Support ongoing changes in student thinking, reflecting the fact that scientific knowledge is generated through human endeavor that can be tested, extended, and used to build new knowledge.
4. Press students for causal explanations of how and why certain phenomena happen and make sure they include evidence and develop conceptual models and representations.

The first instructional practice centers around planning lessons so that they focus on specific phenomena that are illustrative manifestations of DCIs. Research on how people learn demonstrates that students build new knowledge by relating it to what they already know, so the second instructional practice requires that teachers elicit students’ emerging ideas about phenomena. This stage is an essential component of Ambitious Science Teaching and effective science instruction that is not explicitly represented in any of the three dimensions. However, it does relate to the CA NGSS principles of having a coherent curriculum and relating to student interest and prior experience. The third practice ensures that teachers actively engage students, support them, and recognize that changing a preconception takes time. To implement the fourth instructional practice, lessons should provide opportunities for students to generate and interpret evidence (**investigations [SEP-3]** and **analyzing and interpreting data [SEP-4]**) and make their thinking public regarding the development of model-based **explanations [SEP-6]**. In these activities, students can use drawings, diagrams, equations, computer simulations, physical replicas, and more to represent their thinking and make it visible to themselves and others (**developing conceptual models [SEP-2]**). As students engage in activities that require them to modify their models, they develop a deeper understanding of the Nature of Science. Teachers can track their own progression along the continuum of each of these instructional practices using a rubric in Windschitl et al. (2012).

Instructional Strategies for Sequencing Lessons

Different types of instructional strategies can be used during a single lesson or unit depending upon the learning needs of students. The teacher's role varies from the provider of crucial information (e.g., procedural knowledge associated with lab safety requirements or the use of experimental equipment, such as microscopes, measurement tools, and probes) to a learning facilitator (when students are applying science and engineering practices in the context of solving a new problem or explaining a novel phenomenon). This section outlines two sample progressions of lessons throughout a unit. Each follows a consistent pattern in lesson design that promotes three-dimensional learning and engages in Ambitious Science Teaching that aligns with how people learn science. First, we will explain the strategy, then we will demonstrate its use through a snapshot.

Instructional Strategy for 3D Learning: 5E Instructional Cycle

When the sequence of science activities aligns with the way that people learn, students learn more effectively. The science education community has articulated and refined an effective sequence often called the 5E instructional cycle (Bybee et al. 2006). In this cycle, students (1) are *engaged* by some sort of hook that relates to their interest; (2) have time to *explore* ideas on their own before formal instruction; (3) *explain* their observations using models; (4) *elaborate* and *expand* on the new learning by applying it to a new context; and in the end, (5) *evaluate* and reflect on their own learning. Table 11.3 describes these sequences in more detail. The 5E cycle can be effective for sequences of lessons within a multi-week unit, as well as for individual activities within a single day's lesson plan.

Table 11.3. The 5E Instructional Cycle

Engage En	Engage segments pique student curiosity and generate interest through activities that are personally relevant. They bring prior knowledge about the upcoming topics to the forefront and set the focus of future lessons. Teachers employ the first two principles of Ambitious Science Teaching (selecting observable phenomena and eliciting student thinking) as students use the CA NGSS practices of **asking questions [SEP-1]** and performing small **investigations [SEP-3]** (often along with other SEPs).
Explore Ex	The exploration should provide students with a common base of experiences. This can happen through **planning and carrying out active investigations [SEP-3]** or through **obtaining and evaluating information [SEP-8]**. Either way, the activities should facilitate conceptual change by having students experiment, probe, inquire, question, and examine their thinking.
Explain Ex	Based upon their discoveries from the Explore segments, students generate explanations and designs, connecting prior knowledge to new discoveries. Like the CA NGSS practice of **developing explanations [SEP-6]**, students are the ones explaining. The students diagram and verbalize their conceptual understanding, demonstrate their use of science and engineering practices, and apply crosscutting concepts. Teachers can introduce formal labels, definitions, provide direct instruction on essential skills and abilities, and focus student attention on key concepts. Teachers facilitate integration of all these components so that the students can **develop models [SEP-2]** and use them to explain the phenomenon or solve the problem introduced in the Explain segments (the third principle of Ambitious Science Teaching).
Elaborate El	Students apply their new knowledge, skills, and understandings to novel situations in the Elaborate segments. Through new experiences with other phenomena or systems that involve the same scientific concept, the learners transfer what they have learned and develop broader and deeper understanding of concepts about the contextual situation and refine their skills and abilities (the fourth principle of Ambitious Science Teaching).
Evaluate Ev	Learning becomes more active when students have time to reflect on what they have learned. The Evaluate segments include elements for students to evaluate their own learning and the teacher to perform summative evaluation and assessment. Students assess their understanding of phenomenon, success of designs, offer new applications of scientific principles, and inform the next steps for engineering designs. This stage may include embedded assessments that provide feedback about the extent to which students met the CA NGSS performance expectations.

Source: Adapted from Bybee 2013.

In reality, these segments support one another in an iterative spiral more than a direct linear sequence. The Explore and Explain segments often intermingle since students are expected to be seeking explanations during the Explore segment and go back and test their explanations during the Explain segment. Elaborate segments often look very similar to Explore segments as both often involve **conducting investigations [SEP-4]**, but they differ in the amount of teacher support and structure. While Explore segments provide the shared experiences foundation for **constructing models [SEP-2]**, Elaborate segments are more open-ended; students **refine and apply their models [SEP-2]** to novel situations and **solve problems [SEP-6]**. All segments can occur in a variety of learning environments, outdoors and in the community, as well as in the classroom.

Teachers have multifaceted roles in the 5E instructional cycle. As facilitators, they nurture creative thinking, problem solving, interaction, communication, and discovery. Teachers use questions to prompt and expand student thinking, inspire positive attitudes toward learning, motivate, and demonstrate skill-building techniques. As guides, teachers help bridge language gaps and foster individuality, collaboration, and personal growth. Teachers flow in and out of these roles within each segment.

Instructional Strategies Snapshot 11.1: 5E Instructional Cycle for Middle Grades—Newton's Laws

Forces and motion affect students' everyday life, are at the root of classical physics, and are part of the DCI PS1.A: *Forces and Interactions* in the CA NGSS. Before the CA NGSS, Mrs. S, a middle grades teacher, used a "one-dimensional" approach to teaching these ideas. She began with direct instruction on Newton's three Laws of Motion using lecture and a short video presentation. She assigned textbook reading, and then her students performed a variety of short, engaging activities illustrating various aspects of the three laws including the pull-a-table-cloth-off-a-table-filled-with-other-items trick, bouncing balls, rolling things up and down ramps, and swinging objects around their heads. She assigned a lab report requiring students to answer questions about Newton's Laws and the activities, as well as problem sets on the topic. The unit, of course, ended with a quiz. Mrs. S realized that she could use many of the same activities if she changed the order and modified the teacher's role so that they would align with the 5E cycle.

Engage. Mrs. S grabbed her students' attention using a brief demonstration from McCarthy (2005). She embedded a knife blade in an apple just far enough so that the apple stuck to the blade when she lifted the knife. She had students predict what would happen when she gently tapped the back of the knife blade with the blade of a second knife and had them record their ideas in their science notebooks. Then, she began tapping. Following a few taps, the apple was cut in half. The students' responses included

Instructional Strategies Snapshot 11.1:
5E Instructional Cycle for Middle Grades—Newton's Laws

"oohs," "ahs," and "That's really cool." Students discussed in groups what they thought was happening and why. They made diagrams of the system at various moments during the demonstration and explained in words what was happening at that moment. Mrs. S prompted students to use ideas about force and motion from elementary school. Mrs. S listened carefully to assess her students' prior knowledge as well as their preconceived ideas and existing mental models. During a whole-class discussion, Mrs. S highlighted some common ideas she heard but did not comment on whether or not they were "correct" or "incorrect."

Explore. Mrs. S set up two hands-on investigations that previously had come at the end of the unit. She chose these activities because they separated the concepts of velocity and acceleration and developed the necessary language to talk about them. During the activities, Mrs. S employed different "talk moves" to probe students about what they observed, what they thought was happening, and how they might test their explanations.

Explain. After the students had shared common experiences, they were ready to label certain concepts with specific scientifically accepted labels and terminology. Mrs. S used a short mini-lecture to demonstrate how physicists use force diagrams to represent interactions. Students then used these diagrams to represent the systems they had explored in the previous segment. Mrs. S introduced the formal description of Newton's Laws, again through direct instruction (including an instructional video she found). She asked students to determine which of their diagrams best exemplified each of these principles.

Elaborate. Mrs. S had revised her traditional worksheet so that it had more concept-oriented problems, which required students to look at a scenario and use Newton's Laws to predict what would happen. She then set up a design challenge in which students had to apply Newton's Laws to solve a specific problem.

Instructional Strategy Resources: 5E Instructional Cycle

Bybee, Rodger. 2013. Translating the NGSS for Classroom Instruction. Arlington, VA: NSTA Press.
https://www.cde.ca.gov/ci/sc/cf/ch11.asp#link2
Describes steps for translating NGSS expectations into 5E sequences and provides examples from all K–12 levels.

Volkmann, Mark J., and Sandra K. Abell. 2003. "Rethinking Laboratories: Tools for Converting Cookbook Labs into Inquiry." The Science Teacher 70 (6) 38–41.
https://www.cde.ca.gov/ci/sc/cf/ch11.asp#link3.
Provides a checklist and guiding principles for changing lesson sequences so that they better match a 5E-style Instructional Cycle (though 5E is not mentioned explicitly). Focus on secondary-level labs.

Instructional Strategy for 3D Learning: Problem-Based Learning

In problem-based learning (PBL), students work either individually or in cooperative groups to solve challenging problems with real-world applications. Problem-based learning is a subset of *project*-based learning, a process in which students engage in a single thematic topic for an extended amount of time and work toward a specific culmination. Students learn key concepts and content as the need arises in the project or problem-solving process. An authentic real-world context, sustained inquiry, and student self-direction are key components of both strategies.

Problem-based learning is particularly well suited to the CA NGSS because of its focus on **designing solutions [SEP-6]**. In PBL, the teacher poses the problem or challenge, assists when necessary, and monitors progress. As students solve problems, teachers highlight any contradictions between different groups of students and challenge the students to resolve them by coming up with ways to investigate and compare conclusions and solutions. Students must be allowed to make mistakes in PBL, so teachers "need to create a classroom atmosphere that recognizes errors and uncertainties as inevitable features of problem-solving" (Martinez 2010). In PBL, failure and error become recognized as learning opportunities.

Engineering design problems can be the basis for PBL, but science learning must be integrated as an explicit element. For example, students can use trial and error to design a bridge made out of spaghetti strands for an engineering challenge and never deepen their understanding of the three dimensions of the CA NGSS. The challenge can become PBL when students are required to write an **explanation [SEP-6]** that describes what design elements are crucial to the strength of their design (**structure and function [CCC-6]**) and draw diagrams as **models [SEP-2]** of forces within the **system [CCC-4]**. The teacher and students now have a need to introduce and master core ideas and CCCs.

Like the 5E instructional cycle, the key shift of PBL is in the order or sequence in which learning occurs. In 5E, however, engineering challenges were introduced in the "Elaborate" segments as opportunities for students to apply models to new contexts. Problem-based learning shifts the emphasis to solving a problem as the primary goal and learning occurs embedded within the problem solving. In PBL, the problem is introduced at the beginning as the motivation for an entire unit. For example, a high school unit might begin by introducing the problems caused by climate change. During the unit, students will develop solutions that minimize the release of carbon dioxide into the atmosphere from burning fossil fuel. Along the way, they will develop scientific concepts of energy (physics), natural resources (Earth and space science), and fuel (chemistry) to support their development of engineering solutions (which might include energy conservation techniques and alternative energy sources).

Instructional Strategy Resources: Project-Based Learning

While many PBL resources exist on the Web, teachers need to scrutinize them and may need to modify them so that the engaging problem or project also achieves learning in all three NGSS dimensions.

Buck Institute for Education (BIE)
https://www.cde.ca.gov/ci/sc/cf/ch11.asp#link4.
Project-based-learning activity samples and lesson plans with student work samples.

Reinventing Project-Based Learning by Suzie Boss and Jane Krauss
A guide for maximizing the benefits of project-based learning in today's technology-rich environment. This guide is useful for teachers, administrators and professional development specialists.

Instructional Strategy for 3D Learning: Outdoor Learning Experiences

Outdoor and environmental learning experiences are powerful tools for implementing key instructional shifts required by the CA NGSS and California's Environmental Principles and Concepts (EP&Cs). Teachers can effectively use the outdoors as a learning context periodically throughout the year as they teach science. There is also particular value in providing students with longer, concentrated opportunities to explore and explain the natural world by participating in one of California's rich networks of Residential Outdoor Science Schools.

There is wide-ranging evidence to support the value of using natural environments, local communities, and other outdoor settings as a real-world context for science learning that engages student interest as they investigate places around them (Lieberman and Hoody 1998; Lieberman 2013; American Institutes for Research 2005; Glenn 2000). Students should have rich opportunities to observe and investigate the multitude of natural and human social systems found throughout California.

The most effective opportunities to use outdoor environmental learning experiences occur when they are an integral component of three-dimensional science instruction—fully integrated into units of study that do more than offer students isolated out-of-classroom activities. High-quality outdoor and environmental learning is built on research-based instructional strategies like those identified by the BEETLES Project (Lawrence Hall of Science 2017):

- Engaging students directly with nature (for example, on the school campus, at an outdoor science school, or in their community)
- Thinking like a scientist (using NGSS Science and Engineering Practices)

- Learning through discussions (using strategies to promote conversations about science, for example, "talk moves")
- Experiencing instruction based on how people learn (for example, the 5E Instructional Cycle, and using the environment as a context for learning).

Table 11.4 provides examples showing how well-designed outdoor and environmental learning experiences can be used to implement the key instructional shifts of the CA NGSS as students master the ideas represented by California's EP&Cs.

Table 11.4. Achieving the Key Instructional Shifts of CA NGSS and EP&Cs Using Environmental and Outdoor Learning Experiences

Key Instructional Shifts	Examples of Environmental and Outdoor Learning Experiences Supporting the Key Instructional Shifts and California's EP&Cs
Three Dimensional	Natural phenomena found in students' local surroundings provide diverse opportunities to engage in three-dimensional scientific inquiries as they learn the EP&Cs. For example, in fourth grade, students can • undertake a field investigation in the neighborhood [SEP-3], and record the plants and animals they see in their science notebooks [SEP-8]; • look for patterns [CCC-1] in the types and functions of external structures among the different animals [LS1.A]; and, • discover that changes to natural systems can influence [CCC-2] the functioning of plants' and animals' external structures [EP&C II a].
Coherent across the curriculum	Students' investigations of their local community and natural surroundings help them make connections across multiple scientific disciplines, and to read, write, and engage with mathematical analysis, history–social sciences, and technology. For example, middle grades students can • collect weather data [SEP-3] for the area and compare it to long-term climate data collected by the school over 35 years; • ask questions about the data and define a problem [SEP-1] about changes in Earth's climate [ESS3.D] that can be researched using online sources [SEP-8]; • obtain information about the effects temperature changes [CCC-2, CCC-7] have on the snowpack in the Sierra Nevada; • identify human activities that diminish the snowpack in the Sierra Nevada [EP&C IV]; and, • use mathematical thinking [SEP-5] to create meaningful comparisons, using tables and graphs, about the local climate over the past 50 years [history].

Table 11.4. Achieving the Key Instructional Shifts of CA NGSS and EP&Cs Using Environmental and Outdoor Learning Experiences *(continued)*

Key Instructional Shifts	Examples of Environmental and Outdoor Learning Experiences Supporting the Key Instructional Shifts and California's EP&Cs
Relevant to local communities and student interests	Solving real-world problems in their local environment and community gives students the opportunity to learn about issues where they live and then apply what they learn to design engineering solutions that have personal meaning. For example, continuing from above, in the middle grades, students can • identify human activities in their community that release greenhouse gases and influence the global climate [EP&Cs II, IV]; • ask questions to identify evidence [SEP-1] of the possible effects of global climate change [CCC-2, CCC-7] on local habitats and biodiversity [ESS3.C] found in the natural systems at a local wildlife refuge; and, • design possible solutions [ETS.1.B.] to problems caused by local emissions and communicate their findings to the school and community [SEP-8] [EP&Cs V].

Instructional Strategy Resources: Outdoor Learning Experiences

Beetles-Science and Teaching for Field Instructors. 2017. https://www.cde.ca.gov/ci/sc/cf/ch11.asp#link5. Outdoor science education resources that can be used in a wide variety of outdoor science education settings.

Lieberman, Gerald. 2013. *Education and the Environment: Creating Standards-Based Programs in Schools and Districts.* Cambridge: Harvard Education Press.

Yager, Robert, and John Falk, eds. 2007. *Exemplary Science in Informal Education Settings.* Arlington, VA: National Science Teachers Association.

Instructional Strategies for Engaging Student Thinking

Motivation and engagement are essential for the instruction and student learning envisioned by the CA NGSS. What activities catalyze student thinking and motivate students to explore and explain? This section identifies several research-based strategies for helping take student thinking to deeper levels.

Teacher Questioning Strategies: Promoting Science Talk

Humans are social creatures and learn from one another. Well-organized classroom conversations with a range of peers, or “productive science talk,” help students at all levels learn better (Michaels, O’Connor, and Resnick 2008; Michaels and O’Connor 2012). Productive talk is beneficial because it brings prior knowledge to the surface, allows students to reflect on discrepancies between their own thinking and their peers’, and helps them improve their ability to build scientific arguments (NRC 2007b, 92).

Simply providing opportunities for students to talk is not enough. Effective questioning can scaffold student thinking. The NRC (2007a) report offers several research-based suggestions to make questioning more powerful by

- establishing a supportive classroom climate with norms that respect sharing of “first draft thinking”;
- asking questions that are higher-level—questions that require students to analyze, synthesize, and apply information instead of recalling facts;
- providing students with time to think after a question (including “wait time,” writing answers individually, or sharing with partners); and
- explicitly stating that classroom science talk mirrors the practice of professional scientists and frequently reminding students that argument from evidence within a community is part of “doing science.”

Teacher-initiated questions are key to helping students expand their communication, reasoning, arguments, and representation of ideas in science. While the initial questions teachers ask help structure the conversation, follow-up questions are crucial for continuing the conversation. “Talk moves” are follow-up prompts that teachers (or students) can use to invite students to clarify and expand their reasoning and arguments (NRC 2007a, 91). Table 11.5 provides six productive talk moves and examples.

Table 11.5. Examples of Talk Moves

Talk Moves	Example
Re-voicing	"So let me see if I've got your thinking right. You're saying, __________________________?"
Asking students to restate someone else's reasoning	"Please repeat what Ben just said in your own words."
Asking students to apply their own reasoning to someone else's reasoning	"Do you agree or disagree and why?"
Prompting students for further explanation	"What can be added to Mia's idea?"
Asking students to explicate their reasoning	"Why do you think that?" or "What evidence helped you arrive at that answer?" or "Say something more about that."
Using wait time	"Take your time…we'll wait."

Source: Reprinted with permission from NRC 2007a, 92, by the National Academy of Sciences. Courtesy of the National Academies Press, Washington, D.C.

Teachers can provide opportunities for discourse in a range of forums, including partner talk, small-group discussion, and whole-class discussions. These opportunities are only effective when students participate in them. Teachers will need to take the time to cultivate a learning environment where students feel comfortable sharing their ideas and recognize that they are expected to do so. Discussing classroom norms and posting them as reminders in the classroom (as in table 11.6) are the first steps toward building a climate that values discourse. English learners (ELs) may be particularly hesitant to speak up when they struggle with both the ideas and the language to express them. Smaller group and pair discussions allow all students to rehearse their ideas in small groups before sharing them with the whole class. To make these student discussions even more productive, teachers can introduce Talk Moves to students so that they can initiate them with one another. These strategies for improving speaking and listening skills align with the expectations of the California Common Core State Standards for English Language Arts/Literacy (CA CCSS for ELA/Literacy).

Table 11.6. An Example Classroom Sign Designed to Create a Culture of Discourse

Scientists value:	During a science talk, we:	
Mutual respect Attentive listening Openness to new ideas	Take turns Listen to others Keep our eyes on the speaker	Respond to one another Stay focused Disagree respectfully

Source: Provided by Oakland Unified School District.

Instructional Strategy Resources: Engaging Students in Science Talk

Word Generation
https://www.cde.ca.gov/ci/sc/cf/ch11.asp#link6
A more general overview of productive scientific discourse.

The Inquiry Project-Checklist: Goals for Productive Discussions and Nine Talk Moves
https://www.cde.ca.gov/ci/sc/cf/ch11.asp#link7
A more extensive list of talk moves with video examples from classrooms.

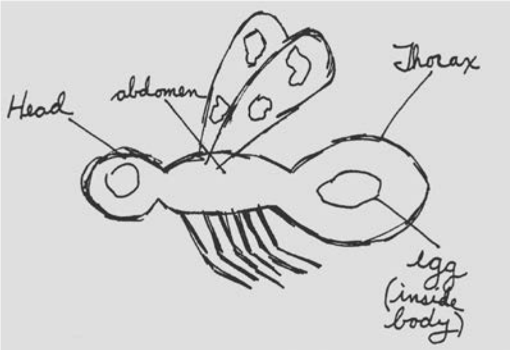
The Inquiry Project Curriculum
https://www.cde.ca.gov/ci/sc/cf/ch11.asp#link8
Free curriculum for grades three through five that includes elements of productive science talk. Includes online professional learning about questioning strategies and science talk and video clips of classroom examples.

University of Pittsburgh Institute for Learning Accountable Talk
https://www.cde.ca.gov/ci/sc/cf/ch11.asp#link9
Online sourcebook of productive talk in all disciplines.

Science and Engineering Notebooks

Scientists keep records of their procedures, thoughts, and findings in a laboratory or field notebook. Student science notebooks are modeled after those of professional scientists and provide a forum for students to make their thinking visible as they engage in all of the SEPs. Students use their science notebooks to develop their ideas and models, reflect on their learning and the questions that they have, plan and record investigations that they make, and communicate their findings. They vary in complexity depending on grade level and can be individual or collaborative (figure 11.1 and figure 11.2). Science notebooks are the place for informal notes and questions as the work proceeds, and formal lab or field reports or other products draw upon information recorded in these notebooks. Table 11.7 describes the benefits of science notebooks.

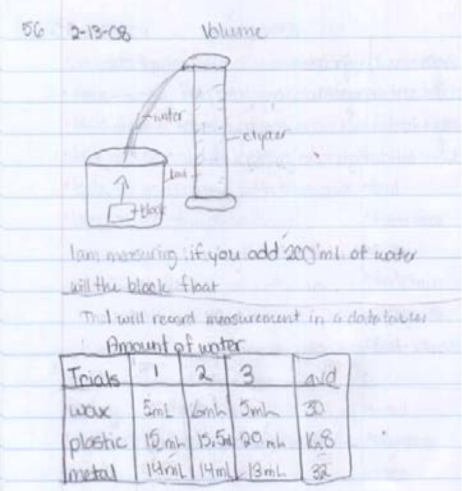
Figure 11.1. An Elementary Student’s Drawing in a Science Notebook



Source: Shepardson and Britsch 1997

Long description of Figure 11.1.

Figure 11.2. Drawing from a Middle Grades Science Notebook



56 2-13-08 Volume

I am measuring : if you add 200 ml of water will the block float

Th I will record measurement in a data table

Amount of water

Trials	1	2	3	avd
wax	5mL	6mL	5mL	30
plastic	15mL	15.5mL	20mL	16.8
metal	14mL	14mL	13mL	32

Source: Washington State LASER and North Cascades and Olympic Science Partnership 2015

Long description of Figure 11.2.

Table 11.7. Benefits of Using Science Notebooks to Support Students' Learning

THE BENEFITS OF USING SCIENCE NOTEBOOKS	
Thinking tools	• Encourage students to use writing for thinking. • Empower students to become active in their own learning.
Guide teacher instruction	• Student notebooks document what students do and do not understand and how they organize their work. • Teachers can use information in the student notebooks to adjust and guide their instruction.
Enhance literacy skills	• Science notebooks provide students the opportunity to engage in various forms of expository writing—e.g., procedural writing, narrative writing, descriptive writing, and labeling. • Science notebooks provide numerous opportunities to develop and enhance students' written, visual, and oral communication skills.
Support differentiated learning	• Science notebooks can be helpful in addressing the needs of students with mixed ability levels in the classroom. • Teachers provide ongoing feedback to students through their science notebooks, allowing the teacher to individualize feedback.
Foster teacher collaboration	• When science notebooks are implemented school wide, teachers have the opportunity to work together and support each other's efforts. • In sharing notebooking strategies and student notebooks, teachers can widen their repertoire with what works best for increasing students' understanding of science.

Source: Adapted from Gilbert and Kotelman 2005.

Science notebooks are a natural link to the CA CCSS for ELA/Literacy as a venue for students to write informative/explanatory texts, but notebooks are useful for much more than just writing. By reviewing hundreds of actual student notebooks, education leaders identified eight distinct strategies or "entry types," used most frequently by practicing K–12 teachers (table 11.8). An online library from Washington State Leadership and Assistance for Science Education Reform (LASER) includes multiple samples of each entry type by students of all grade levels, demographic groups, and geographic regions (for more detail see Washington State LASER and North Cascades and Olympic Science Partnership 2015).

Table 11.8. Types of Entries in Science Notebooks

ENTRY TYPE	DEFINITION AND PURPOSE
Drawings	Definition: Student-generated drawings of materials, scientific investigation set-up, observations, or concepts Three common types of drawings used in science notebooks include a) sketches—informal pictures of objects or concepts created with little detail; b) scientific Illustrations—detailed, accurate, labeled drawings of observations or concepts; and c) technical drawings—a record of a product in such detail that someone could create the product from the drawings.
	Purpose: Students use drawings to make their thinking and observations of concrete or abstract ideas visible. Drawings access diverse learning styles, allow entry to the writing process for special needs students and emergent writers, and assist in vocabulary development (e.g., oral explanations, group discussions, labels).
Tables, Charts, and Graphs	Definition: Formats for recording and organizing data, results, and observations
	Purpose: Students use tables and charts to organize information in a form that is easily read and understood. Recording data in these forms facilitates record keeping. Students use graphs to compare and analyze data, display patterns and trends, and synthesize information to communicate results.
Graphic Organizers	Definition: Tools that illustrate connections among and between ideas, objects, and information Examples include, but are not limited to, Venn diagrams, “Box” and “T” charts, and concept maps.
	Purpose: Graphic organizers help students organize ideas to recognize and to communicate connections and relationships.
Notes and Practice Problems	Definition: A record of ideas, observations, or descriptions of information from multiple sources including, but not limited to, direct instruction, hands-on experiences, videos, readings, research, demonstrations, solving equations, responding to guiding questions, or developing vocabulary
	Purpose: Students use notes and practice problems to construct meaning and practice skills for current use and future reference.

Table 11.8. Types of Entries in Science Notebooks *(continued)*

ENTRY TYPE	DEFINITION AND PURPOSE
Reflective Analytical Entries	Definition: A record of a student's own thoughts and ideas including, but not limited to, initial ideas, self-generated questions, reflections, data analysis, reactions, application of knowledge to new situations, and conclusions
	Purpose: Students use reflective and analytical entries to think about scientific content from their own perspective, make sense of data, ask questions about their ideas and learning processes, and clarify and revise their thinking.
Inserts	Definition: Inserts are artifacts placed within a notebook including, but not limited to, photographs, materials (e.g., flower petals, crystals, chromatography results), and supplemental readings (e.g., newspaper clippings)
	Purpose: Students use inserts to document and to enrich their learning. Personalization of science notebooks also serves to push students to take ownership of their learning process.
Investigation Formats	Definition: Scaffolds to guide students through a controlled investigation, field investigation, or design process Examples include, but are not limited to, investigation planning sheets or science writing heuristics.
	Purpose: Students use investigation formats to guide their thinking and writing while they design and conduct investigations. Students also use these formats to reflect on, modify, and discuss their findings and ideas.
Writing Frames	Definition: Writing prompts used to focus a student's thinking Examples include, but are not limited to, I smelled . . . I felt . . . I observed . . . I noticed . . . I wonder . . . , It reminds me of . . . , I noticed a difference between . . . , My results show . . . , The variable I will change is . . . , or I think that because . . .
	Purpose: Students use frames to organize their ideas, prompt their thinking, and structure their written responses. Frames help students become more proficient in scientific writing and less reliant upon the prompts.

Source: Adapted from Washington State LASER 2016.

Instructional Strategy Resources: Science Notebooks

Professional Learning Module for Common Core State Standard Literacy in Science
https://www.cde.ca.gov/ci/sc/cf/ch11.asp#link10
An overview of how to use science notebooks in the classroom as a formative assessment tool to recognize students' sense-making of scientific ideas

Engineering Notebooks

Engineering notebooks share common entry types with science but also include engineering-specific entry types. Engineering design projects are often conducted as teams, so the notebook needs to include a record of team decisions from each step of the project. Each student may keep a notebook or one student may keep a team notebook. Entries may include

- introduction, including the date, names of the group members and, if applicable, the name of the person keeping the group notebook;
- the problem to be solved;
- criteria, constraints, and priorities;
- summaries of information-gathering about the problem, constraints, or possible materials;
- relevant principles and scientific knowledge;
- possible solutions, including ideas from brainstorming and pros and cons of each;
- a decision matrix (Pugh Chart) or other means to select the design(s) to test;
- proposed solution(s) and a description of the prototype;
- results of testing the solution, including a description of the tests used;
- evaluation of the best proposed solution, including both pro and con information about its suitability to solve the problem;
- design improvements based on the results of the evaluation; and
- presentation of the final design, with a description of why it is a good design, any shortcomings, and ideas for improvement.

Instructional Strategy Resources: Engineering Notebooks

Wikibooks. Writing patterns for engineering notebooks
https://www.cde.ca.gov/ci/sc/cf/ch11.asp#link11.

Oregon Department of Education. Design It! Template
https://www.cde.ca.gov/ci/sc/cf/ch11.asp#link12.
Template for middle grades design notebook

Oregon Department of Education, Design It! Instructions
https://www.cde.ca.gov/ci/sc/cf/ch11.asp#link13.
Instructions for using the Oregon middle grades design notebook template

Discrepant Events

A discrepant event is something surprising—it's an example of a phenomenon in which something happens that contradicts students' intuition and mental models about the physical world. Discrepant events pique curiosity and motivate students to use problem-solving and critical-thinking skills to explain that phenomenon. They provide particularly powerful learning experiences because they force students to confront their prior knowledge and see that it is insufficient to explain the current situation. Discrepant events encapsulate the experience of professional scientists, and present students with the same puzzling phenomena that led to major discoveries in the past, placing these activities in historical context.

Teaching a discrepant event is more than just showing a demo or telling a story with unexpected results. Table 11.9 outlines an intentional sequence to maximize the learning potential of discrepant events. This sequence of learning has often been called "teaching for conceptual change" (Chinn and Brewer 1993). Confronting discrepant events provides rich opportunities for students to engage in **modeling [SEP-2]** and the discourse-focused practices of **explanations [SEP-6]** and **arguments [SEP-7]**.

Table 11.9. Steps for Effective Learning from Discrepant Events

STEP	PRACTICE AND ROLE IN LEARNING
1. Consider a physical scenario whose outcome is not known.	Set the context.
2. Predict the outcome.	Apply existing mental models. Make prior conceptions public.

Table 11.9. Steps for Effective Learning from Discrepant Events *(continued)*

STEP	PRACTICE AND ROLE IN LEARNING
3. Construct models and explanations to support the predictions.	Convert existing mental model into a conceptual **model [SEP-2]** that can be discussed.
4. Observe the outcome.	**Perform an investigation [SEP-4]**.
5. Modify competing theoretical explanations, if necessary.	**Refine models [SEP-2]**. **Construct explanations [SEP-6]**.
6. Evaluate competing explanations.	**Engage in argument from evidence [SEP-7]**.
7. Reiterate the preceding steps with different data.	Reflect on learning and then apply the revised model to a new context to solidify understanding.

Discrepant events can be observed directly in class or using videos easily available from the Internet. Video offers the opportunity to pause at critical points during the demonstration, provide an opportunity for students to predict what could happen next, and re-play portions of the demonstration as students walk through the discrepant-event sequence. This approach provides students with additional evidence for discussion and reflection on how their thinking is changing.

Instructional Strategies Snapshot 11.2:
Discrepant Event Demonstration*

When students arrived to class, there was a large glass bowl containing water on a table at the front of the class. A candle, standing upright in the middle of the bowl and held in place by clay, stuck out well above the water. A large empty flask and some matches were beside the bowl.

Ms. N told her students that she would light the candle and then turn the large flask upside down and put it over the candle. She asked them to write down what they think would happen and why. In addition to writing a description, they needed to draw a picture of what would happen.

Ms. N knew that most students would predict that the candle would go out, thinking the candle would consume the oxygen in the container. Having them write their predictions out gave students a record of their old thinking, gave the experience more personal value as they tested out their own ideas, and made the surprising result more powerful.

Instructional Strategies Snapshot 11.2: Discrepant Event Demonstration*

After students finished writing and drawing, Ms. N lit the candle and placed the flask over the candle with its opening under water. An excited murmur erupted in the class. The candle did indeed go out, but to the surprise of the students, the water also rose inside the neck of the flask.

Student 1: No way . . . did you see that?

Teacher: What did you see?

Student 1: The flame went out just like I said it would.

Student 2: Yeah, but the water rose, too.

[Other students voice their agreement with this second observation.]

Teacher: Why do you think that happened?

Student 3: The oxygen got used up and created a vacuum that sucked up the water.

Student 4: I agree; oxygen was used up. Burning uses oxygen, so when the oxygen was gone, the flame went out.

Student 5: I thought we learned that vacuums don't suck, so I don't think the water got *sucked* up the flask.

Student 3: Well, I still think there was a vacuum created when the oxygen got used up and when that happened the water rose.

Teacher: What other explanation could we have for this phenomenon?

[After looking around the room and hearing no comments, Ms. N continued.]

Teacher: It appears that you all agree that a vacuum caused by fewer oxygen molecules is the cause. Please go and modify your explanations and drawings to capture this idea.

Ms. N's students were familiar with revisiting their thinking. Throughout their study of physical science, Ms. N's students had created models to understand the world and revisited those models over and over as they refined their thinking. It was sometimes frustrating for students who just wanted to be told the correct answer, but Ms. N is consistent in making students write, draw, and revise.

Next she asked the students, "What do you think would happen if I used two candles instead of one?" Students said that the candles would go out faster because they would use up the oxygen faster. When pressed, they believed the water would still rise, but it would rise the same amount as before. After all, it was the same amount of oxygen getting used up, so it would be the same size vacuum being produced.

Ms. N asked students to once again write down a prediction and their thinking. While they wrote, she placed a second candle in the bowl. When students finished writing, she repeated the demonstration using two candles instead of one. The candles went out as they expected, but they were also surprised to see that the water rose to a higher level than before.

Teacher: Tell me what you are thinking now.

Student 4: The water went up higher. That doesn't make any sense to me. If it's the same amount of oxygen, shouldn't it have only gone up the same amount?

Instructional Strategies Snapshot 11.2: Discrepant Event Demonstration*

Student 5: Let's do it again with only one candle. Maybe the water rose up over the wick, and that made the candle go out before it used up all the oxygen.

Student 6: Maybe because there were more candles, it pulled oxygen from the water. You know water is H_2O, so maybe since there were extra candles, they needed extra oxygen and got it there.

Student 7: That's not possible. The oxygen in water is bonded to the hydrogen. It won't just come apart. If that were the case, candles would burn under water.

Student 8: The candles did go out faster this time than last time. I think that's because they used up the oxygen inside the flask faster.

Student 7: I agree with that. I don't understand why the water went up higher though. That doesn't make sense to me.

Teacher: What do you think would happen if we used more than two candles?

Student 7: The candles would still go out and the water would rise even higher.

Teacher: Why do you think that?

Student 7: I have no idea. I just think if it went up more with the two than one, it should go up more if you used more than two.

Teacher: I am going to put you into teams to design an experiment that will help you answer the question about what makes the water rise. Before I give you any equipment, you will need to write out your procedure. It must address the questions and your current thinking about the answer.

As the students designed and conducted investigations, Ms. N circulated between groups. She asked questions which guided student observation, thinking, and meaning-making. She started with questions about what they observed, helping them notice the bubbles escaping from the flask—even prompting them to add a drop of liquid soap to their bowl of water to make the bubbles more visible. She challenged them to reconcile the idea that more candles make the water rise higher than fewer candles, yet the amount of air inside the flask does not change. In this activity, students explored an authentic scientific problem, developed models to describe what happened, and tested those models. Ms. N was not concerned about students arriving at the "correct answer" (which is quite complicated), but rather that they were able to explain all their observations with a consistent model. As she circulated, she moved students closer to the scientifically accepted explanation by suggesting specific tests or pointing out inconsistencies in their models (i.e., "That sounds good, but your model doesn't explain . . ."). Ms. N challenged the groups that developed consistent models more quickly to find other ways to make the water rise that would not involve lighting candles. In the end, Ms. N did not tell her students the "right" answer but congratulated each team on coming up with a consistent model. Students really wanted confirmation that their model was right, but she reminded them that there is no "answer key" in real science.

*This discrepant-event demonstration pairs with the classroom case study #1 described in appendix D of the CA NGSS.

Instructional Strategies for Teaching the Nature of Science

The science education community uses the phrase “nature of science” to refer to what science is and how science works. Discussions of the nature of science also address issues related to the historical, social, cultural, and ethical aspects of science. Explicitly drawing attention to these issues fosters student appreciation for how scientists know what they know and the intrinsic limitations of that knowledge. Appendix H of the CA NGSS presents eight broad understandings about the nature of science that teachers should refer to in much the same way that they explicitly teach the SEPs and CCCs (table 11.10).

Inquiry-based lab activities where students engage in the science and engineering practices are not the same as activities in which students are also learning about the nature of science. The most effective strategy for teaching about the nature of science is to make explicit connections to it within the context of each lesson.

Table 11.10. Eight Understandings about the Nature of Science in CA NGSS

Related to Science and Engineering Practices	Related to Crosscutting Concepts
• Scientific Investigations Use a Variety of Methods • Scientific Knowledge is Based on Empirical Evidence • Scientific Knowledge is Open to Revision in Light of New Evidence • Scientific Models, Laws, Mechanisms, and Theories Explain Natural Phenomena	• Science is a Way of Knowing • Scientific Knowledge Assumes an Order and Consistency in Natural Systems • Science is a Human Endeavor • Science Addresses Questions About the Natural and Material World

Source: NGSS Lead States 2013a

Using Historical Case Studies to Teach Science

> *Teaching science and engineering without reference to their rich variety of human stories, to the puzzles of the past and how they were solved . . . would isolate science and engineering from their human roots, undervalue their intellectual and creative contributions, and diminish many students’ interest.*
>
> —National Research Council, *A Framework for K–12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*

Science has always been a human endeavor. Showing this historical journey allows teachers to highlight the process of science rather than just its products. Historical cases can also provide insight into those products as students learn about historical observations in the same progression that they might experience experimental results in hands-on laboratories. Table 11.11 introduces a few examples of historical cases appropriate for different learning goals or contexts.

Table 11.11. Examples of Historical Case Studies Related to Specific Learning Contexts

Context for using historical case studies	Reasons to use the context
Celebrating discoveries and great scientists: Exemplifying the value of science and portraying role models	Popular culture depicts a distorted image of scientists. Establishing diverse role models helps students envision the possibility that they, too, could become a scientist or engineer. Examples of role models include Marie Curie and her discovery of radioactivity and its use in battlefield radiological units during World War I; Rachel Carson and her contribution to the development of the modern environmental movement; and George Alcorn and his re-engineering of the imaging x-ray spectrometer.
The impact of science on society and the environment	Rachel Carson's scientific studies of the effects of pesticides on the environment, published in her book *Silent Spring,* led to the development of the modern environmental movement.
Providing developmental themes and story lines	Discoveries may also be addressed in the context of their conceptual development throughout history. An illustrative example is that of the English doctor John Snow and his explanation of contagious illnesses or the history of the understanding of the atom over hundreds of years.
Teaching the process of science	The history of science allows students to appreciate how concepts emerge through a nonlinear process that often includes ambiguity, dramatic sudden insights, or deliberate investigations, sometimes very gradually and with great difficulty. Examples that may be addressed in this context include Gregor Mendel's theory of inheritance, Dimitri Mendeleev's arguments for new elements based on his periodic table and subsequent discoveries, and Alfred Wegner's proposal of a causal explanation involving the slow displacement of continents, and Walter Alvarez's evidence for a large asteroid wiping out the dinosaurs.
Teaching the role of engineering and technology on scientific discovery	The Hubble Space Telescope allowed astronomers to finally answer Hubble's fundamental questions about the expansion of the universe 50 years after he died. Devices that rapidly sequence DNA have revolutionized evolutionary biology by allowing geneticists to study the tiny changes of individual genes.

Table 11.11. Examples of Historical Case Studies Related to Specific Learning Contexts *(continued)*

Context for using historical case studies	Reasons to use the context
Teaching the role of science in technological change	There are many examples of scientific discoveries that enabled technologies that changed the world, such as the role of nuclear physics in developing weapons and as a means of generating electrical energy.
Teaching concepts	Historical episodes often model how students may actively reconstruct concepts on their own. They show how specific ideas may emerge given certain conceptual resources, questions, and opportunities to investigate. For example, providing a historical sequence of information that contributed to the discovery of the most likely structure of DNA allows giving an in-depth justification of the blueprint for life.
Teaching about conceptual change	The history of science is not merely about how a concept originated, rather it may be about how a theory is completely revolutionized as new evidence and thinking are brought to light. These dramatic shifts in worldview are exemplified in the Copernican and Darwinian revolutions in which extreme reconceptualization of, respectively, the position of Earth with respect to the universe and the origin of differentiation in species (including humans) are presented.
Showing the “human” dimension to science	Science and engineering are activities conducted by real people with real lives. Climate scientist James Hansen’s concern about the future of his grandchildren motivates his work. Chimpanzee sign language experts Roger and Deborah Fouts are lifetime collaborators in science and in marriage—using each role to strengthen the other. Brian May (lead guitarist for Queen) and Dexter Holland (lead singer of the punk band The Offspring) were both graduate students in science when their bands took off. May used his background in physics to build his first electric guitar, which he still uses in concerts today. Actress Mayim Bialik, who plays a scientist on the TV comedy Big Bang Theory, actually has a Ph.D. in neuroscience and uses it to make the show funnier.
Highlighting the cultural basis of ideas and research	The message about the human context of science can sometimes be extended to highlight its broader social dimensions. History provides examples of how scientific ideas have realigned cultural attitudes, even world views, and how technologies have materially affected industry, labor, lifestyles, etc.

Instructional Strategy Resources: Natural Science

Understanding Science
https://www.cde.ca.gov/ci/sc/cf/ch11.asp#link14

"History as a Tool in Science Education" by Douglas Allchin https://www.cde.ca.gov/ci/sc/cf/ch11.asp#link15

The Story Behind the Science (2006)
https://www.cde.ca.gov/ci/sc/cf/ch11.asp#link16

Harvard Case Histories in Experimental Science (1957)
https://www.cde.ca.gov/ci/sc/cf/ch11.asp#link17

actionbioscience, Historical Case Studies (2014)
https://www.cde.ca.gov/ci/sc/cf/ch11.asp#link18

Famous Black Inventors (2008)
https://www.cde.ca.gov/ci/sc/cf/ch11.asp#link19

Women in Science, Technology, Engineering and Mathematics (2014) https://www.cde.ca.gov/ci/sc/cf/ch11.asp#link20

Instructional Strategies Snapshot 11.3: Scientific Methods and the Nature of Science

Part 1: Before the CA NGSS

First, let's look at Ms. A's classroom before the CA NGSS. Ms. A used many effective instructional strategies but was not yet capturing the full three-dimensional vision of the CA NGSS.

Ms. A had carefully prepared her classroom. Laboratory cabinets were cleaned and well stocked, colorful fish were darting about an aquarium bubbling on the side of the room, and posters depicting famous scientists were everywhere. Ms. A hoped students would identify with one or more of the scientists.

In the first week of school, Ms. A told her high school students they would be "learning about the scientific method, the basis for all science." "The method," she explained, "has seven steps." Jotting them down on her whiteboard, she told students that scientists must do the following:

1. Make observations.
2. Ask a question about something they observed.
3. Do background research about their question.
4. Construct a hypothesis, or educated guess, about the answer to their question.
5. Test their hypothesis by doing an experiment.
6. Analyze their data and draw a conclusion.
7. Communicate their results.

Instructional Strategies Snapshot 11.3: Scientific Methods and the Nature of Science

To help students see how this works, she assigned them a passage to read about a nineteenth-century English doctor named John Snow (1813–1858, English physician and pioneer of the field of modern epidemiology). Snow lived in London at a time when everyone believed contagious illnesses were spread through the air (the disease malaria literally means "bad air"). He challenged this idea in the wake of an 1854 cholera epidemic in London.

Snow went door to door in a particularly hard-hit part of town, interviewing residents about the illness in their household, trying to trace the disease back to what would today be called "patient zero." He carefully plotted his data on a map of the town of London, eventually tracing the illness to a single water pump. People in the neighborhood who drank from this pump became ill; those who didn't drink from the pump remained well.

Ms. A handed out a worksheet with a list of the seven steps in the scientific method, with space next to each step. Students were instructed to read the story, and, with a partner, fill in what Snow did for each of the scientific method's seven steps.

The next day, Ms. A went over the expected responses for the assignment. Afterwards, Ms. A's students moved on to their first laboratory. She reinforced the previous day's lesson by telling students about the lab reports she expected them to complete, which included the seven steps in the scientific method. She expected students to write the lab's question, hypothesis, procedure, data generated, and an analysis of the data.

Ms. A had started her class this way for years. She did not spend the whole first day lecturing, and she found a way to encourage students to work together at the very beginning of the year. Her students began working on a lab activity by the second day of the year and were engaged in an interesting story from the beginning.

Part 2: After the CA NGSS—What shifts should Ms. A make?

With a few changes, Ms. A's lesson could be more effective at helping her students understand what science is and how science works. The most dramatic shift would be changing her emphasis on "the" scientific method. Indeed, no single and linear scientific method exists as scientific investigations use a variety of methods. A geologist observing rocks or a biologist observing plant distributions in nature uses different methods than an experimental physicist or molecular biologist working in a controlled laboratory setting.

In reality, John Snow probably had ideas about how cholera spread (step 4, construct a hypothesis) before he noticed what was happening in his London neighborhood (step 1, make observations). Snow's ideas or explanations about cholera spreading through water were not necessarily predictions—a hypothesis is not a prediction or necessarily an "educated guess" (step 4 again). When he began talking to people to map the disease's spread, was he *testing* a hypothesis at this point (step 5) or was he doing work that ultimately *led* to a hypothesis about how the disease was spread (steps 1-3)?

Instructional Strategies Snapshot 11.3: Scientific Methods and the Nature of Science

While scientists do engage in practices like the ones in Ms. A's list, they can occur in many different sequences. Sometimes scientists reason *inductively,* collecting observations first and then recognizing patterns in their data to help them create new models and new ideas. Other times they reason *deductively* as they collect observations to test their ideas. The methods scientists use to create ideas often differ from those they use to test ideas. In other words, there are scientific *methods,* but no single, universal scientific *method*.

So what should Ms. A teach her students if she is not going to tell them about "the" scientific method? Ms. A could focus her case study on the principle that scientific knowledge is based on empirical evidence. Ms. A could reiterate how most people at the time believed illnesses like cholera were spread through the air. The conclusion seemed obvious. Illness and bad smells went hand in hand, and few at that time would believe drinking a few ounces of water could make one sick. Despite his data, Snow's ideas were rejected. Ms. A could use this historical observation to highlight science as human endeavor and as such constrained to the limitations of human society. Nevertheless, Snow and those who followed eventually convinced the scientific community that diseases could be spread by water. One of the hallmarks of science, one of the things that separates science from other ways of knowing, is that scientific knowledge is open to revision in light of new evidence.

The case study of John Snow illustrates all eight of the CA NGSS elements of the nature of science (table 11.10). In fact, the eight elements are so central to science that just about *any* scientific case study will illustrate the points. There is, however, an important caveat to add to the discussion. Having students read a case study, see a video about John Snow, look at a copy of his famous "ghost map," or even discuss the case in class will *not* (by itself) help them understand the nature of science. Students will only rarely recognize the ideas for themselves. Teachers are most effective at helping students understand the nature of science when they (a) provide activities or assignments illustrating nature-of-science elements; (b) explicitly help students recognize, understand, and apply the ideas; and (c) do so throughout the school year. Whether presenting a historical case study, a contemporary example of science work, or a laboratory activity in which students are engaging in science practices or illustrating crosscutting concepts, Ms. A could

- use a moment of whole-class direct instruction to point out, or prompt students to point out, how the activity illustrates particular elements of the nature of science;
- prompt discussion among small groups of students about how their work illustrates nature-of-science elements; or
- assign readings (or other extensions) and ask students to figure out how the assignment material illustrates nature-of-science elements.

Instructional Strategies Snapshot 11.3: Scientific Methods and the Nature of Science

Resource

A Web page from the UCLA School of Public Health provides a summary of John Snow's life and primary sources of documents related to the work of John Snow, including his historical discussion of the development of his thinking about cholera in London during the period of 1843-1855. See https://www.cde.ca.gov/ci/sc/cf/ch11.asp#link21.

Instructional Strategies Snapshot 11.4: Teaching the Nature of Science Explicitly

Ms. B's middle grades Earth science class was conducting a hands-on investigation of chemical weathering. Students dissolved chalky antacid tablets in water to simulate the effects of water on rock over time. Students timed how long it took a tablet to dissolve in cold water (part one of the activity), and then repeated the process in warm water (part two). Ms. B showed them exactly how to perform the procedure, record their data, and display their results in a graph. Before the CA NGSS, she would have finished the lesson with a short worksheet about the graph, but this year she decided to extend the activity so that students explicitly discussed the nature of science.

She asked groups of students to display their results on chart paper. Most looked similar, but it soon became apparent that a few groups' results differed from those of their classmates. Ms. B did not tell any groups their results were "wrong." Instead she told the class that science assumes that repeating an experimental procedure in *exactly* the same way will produce similar results, i.e., scientific knowledge assumes an order and consistency in natural systems. If groups got different results, they must have done something different from one another, even if they didn't intend to. The difference in results provides a good opportunity to have students engage in **argumentation [SEP-8]** through oral discussion. Ms. B paired groups with different results and asked students to figure out where their procedures may have differed.

Next, Ms. B asked the rest of the class for thoughts about other things (*variables*) that might make an antacid tablet dissolve faster or slower. When a student called out a variable, she wrote it on the whiteboard, asking the student whether they thought the variable would speed or slow the reaction and why it would have that effect.

After the students had generated a long list, she said, "One of the things separating science from other ways we understand the world is that science demands evidence. Scientific knowledge is not based just on people's opinions; it is the result of testing." After crossing out variables that could not be safely or logistically investigated in the

Instructional Strategies Snapshot 11.4: Teaching the Nature of Science Explicitly

student-centered learning environment, she told students to select a variable of interest and get ready to test whether they could accurately predict the variable's effect on antacid dissolving speed. By explicitly drawing attention to the fact that science is a way of knowing, and scientific knowledge is based on empirical evidence, students really began to understand what Ms. B says when she tells them, "In this activity, you are scientists."

Before the students began their investigations, Ms. B asked the class about things students needed to do for their investigations to be "fair," i.e., variable control. She ensured that students agree to a common technique to measure their results **quantitatively [CCC-3]** so that they could easily compare them (rather than just saying, faster or slower). Students ultimately returned to their lab areas and performed their own investigations. By using essentially the same materials they just used in the initial investigation, students successfully **planned and carried out their investigations [SEP-3]**.

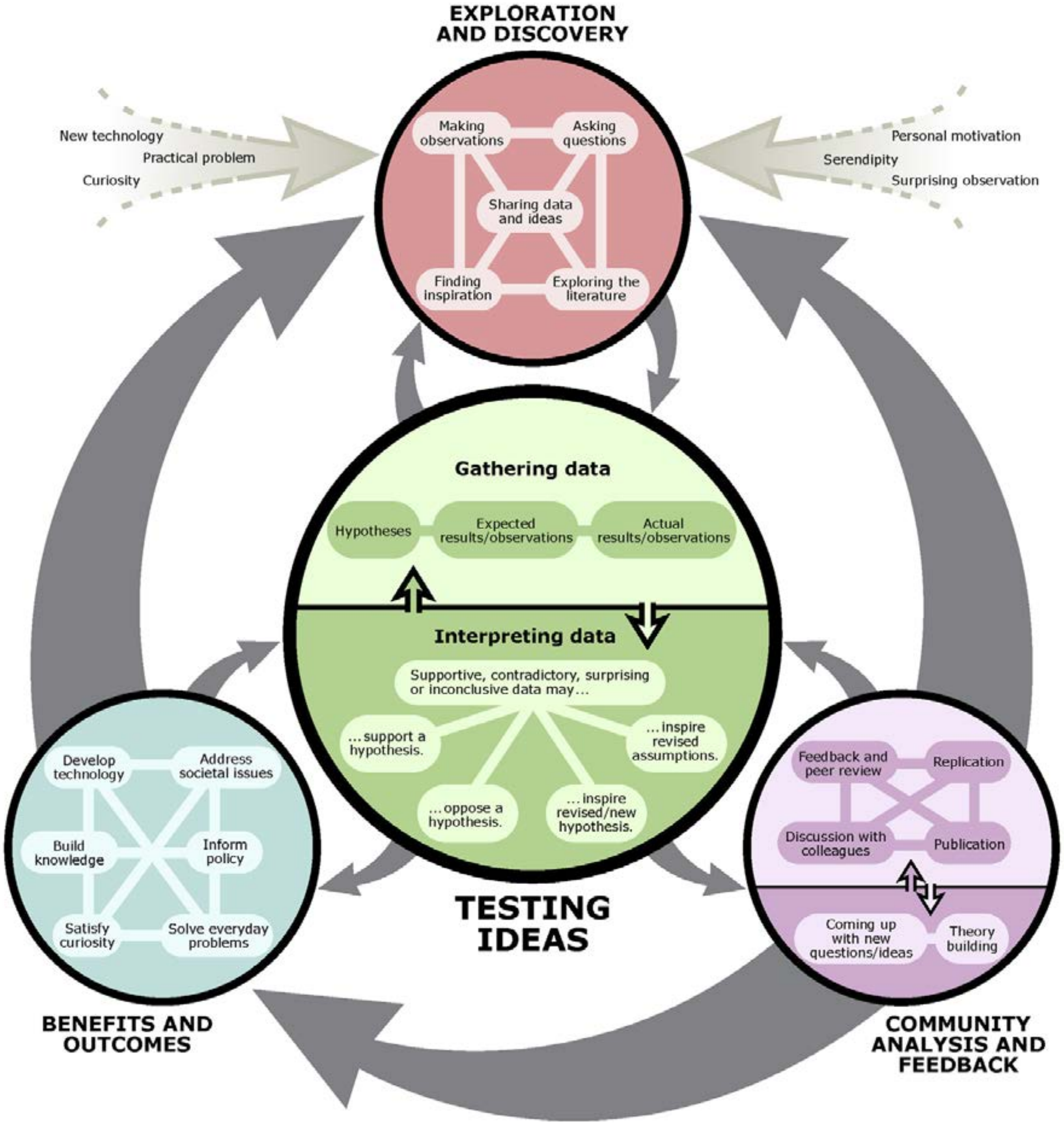
When multiple groups investigated the same question but came to different conclusions, Ms. B emphasized that science is a human endeavor; disparate results are common; and scientists ultimately resolve these kinds of issues through a combination of communication, data sharing, and sometimes further investigations.

When students were surprised by results, she pointed out how scientific knowledge is open to revision in light of new evidence. She told the students, "You have to go where your data takes you," and "It is common for scientific ideas to change."

As results came in, Ms. B asked students, "How did your variable affect the tablet? What did it do that **caused [CCC-2]** a change?" When she heard students with the same data provide different explanations, she pointed out how different students can look at the same **patterns [CCC-1]** in data and construct different interpretations of the data. To figure out which was the "right" explanation would require the students to ask more questions about how the ideas might differ, and then perform a different test to collect enough observations to answer them.

At the end of the activity, Ms. B asked students to chart their journey through different stages of the process of science (figure 11.3, Understanding Science 2016).

Figure 11.3. Representation of the Process of Science as a Nonlinear Complex Endeavor



Source: Understanding Science 2016.
Long description of Figure 11.3.

The nature of science concepts from appendix H of the CA NGSS, like the other SEPs and CCCs, follow a developmental progression. Elementary students should be learning explicitly about what science means, but do so in a developmentally appropriate manner that lays a foundation to be built on in later grades.

Instructional Strategies Snapshot 11.5: The Nature of Science in Elementary School

Mr. C started the investigation with the question, “What happens when we leave ice out?” Mr. C then told the children they “would be scientists for the day,” and “Science starts with questions.”

Mr. C handed every student an ice cube and had the students sit in groups to observe them melting. Mr. C encouraged students to look at their own ice cube and the other ice cubes in their groups to notice that similar things happened to all of them. Mr. C told students that scientists pay close attention to things that happen the same way over and over again. Mr. C explicitly introduced the idea of **patterns [CCC-1]**, which provides the K–2 foundation for the broader nature-of-science topic that “scientific knowledge is based on empirical evidence.”

Mr. C asked students to record new things that they learned and told them that they were “acting like scientists because that is how science works—when new information comes in, we change our thinking.” Mr. C also had students draw what they saw, “because scientists use drawings to tell people about what they saw.” He was drawing attention to how scientists use models to explain new phenomena and communicate those findings to others. At the K–2 level, a simple diagram is an example of a pictorial model that communicates.

When he said, “Today we learned about how ice melts and becomes liquid water. Science helps us know about the world,” he was helping them learn that science is a way of knowing. If he had pointed out, “We did not just look at one ice cube. We looked at lots of ice cubes,” he would have been helping them understand that scientific knowledge assumes an order and consistency in natural systems. He helped the children recognize science is a human endeavor when he said, “Lots of people become scientists. People just like you!”

Instructional Strategies for Teaching the Engineering Design Process

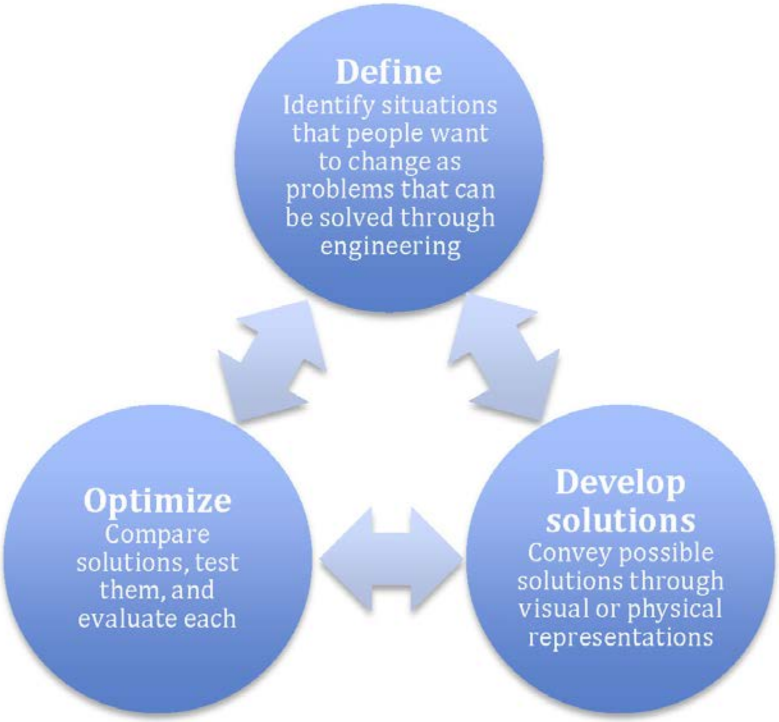
The emphasis on engineering in the CA NGSS ensures that students develop the knowledge and skills to solve problems. The most important instructional strategy is therefore to select topics that are relevant to local communities and emphasize the relationship between science, technology, engineering, and society. As students explore these challenges, they can see themselves as problem solvers, inventors, and discoverers.

Explicitly Teaching the Engineering Design Cycle

As with the nature of science, students benefit from explicit discussion of engineering practices. Just as there is no single scientific method, there is no single engineering design process (Crismond et al. 2013). Nonetheless, CA NGSS identifies three key "phases" that engineers cycle through as they solve problems (figure 11.4; appendix I of the CA NGSS):

- *Defining and delimiting engineering problems* involves stating the problem to be solved as clearly as possible in terms of criteria for success and constraints or limits and other aspects of the design such as cost, weight, durability, etc.
- *Designing solutions to engineering problems* begins with generating a number of different possible solutions, then evaluating potential solutions to see which ones best meet the criteria and constraints of the problem.
- *Optimizing the design solution* involves a process in which solutions are systematically tested and refined, and the final design is improved by trading off less important features for those that are more important.

Figure 11.4. NGSS Engineering Design Process



Source: NGSS Lead States 2013b
Long description of Figure 11.4.

Some engineering educators prefer to subdivide these stages into more detailed descriptions of behaviors, including

1. clearly identifying the problem, including defining any necessary physical or economic constraints on the desired solution;
2. brainstorming multiple possible solutions;
3. researching what others have done with similar problems and, through preliminary analysis, eliminating any solutions that may not be practical;
4. designing and fabricating a prototype;
5. testing the prototype to verify that it solves the problem and optimizing that prototype for efficiency, comfort, ease of use, etc.; and
6. communicating the results through presentation, competition, peer review.

The varying degrees of detail in different depictions of the engineering design cycle highlight the fact that engineering practices follow a developmental progression through different grade spans (appendix I of the CA NGSS). The grade-span sections below illustrate this progression using snapshots.

Grades K–2

Engineering design in the earliest grades introduces students to “problems” as situations that people want to change. They can use tools and materials to solve simple problems, use different representations to convey solutions, and compare different solutions to a problem and determine which is best. The emphasis is on thinking through the needs or goals that need to be met and which solutions best meet those needs and goals.

Instructional Strategies Snapshot 11.6: Engineering Design K–2

Mr. Z, a second-grade teacher, used an enrichment unit from Engineering Is Elementary that provides lesson plans combining social studies, reading, and science. The students began by reading the storybook *Mariana Becomes a Butterfly* (Engineering is Elementary 2008), in which the main character, Mariana, a girl from the Dominican Republic, is puzzled by a change in one of her garden plants, which a friend brought to her from Hawaii. At first, it produced delicious berries, but now Mariana cannot get any berries to grow. With the help of her Tía (Aunt) Leti, an agricultural engineer, Mariana soon discovered the problem: in its new surroundings, the plant lacked a pollinator. Mr. Z demonstrated pollination with a paper model of a flower, pointing out the male part (stamen) and female part (pistil), and explaining what the pollinator must accomplish. In the next lesson, the students put on a play to learn about the ways that some insects help farmers through pollination and other insects cause problems. The play also introduced ways that agricultural engineers help solve these problems.

“Do you remember Mariana’s problem? Why do you think the plant that her friend brought from Hawaii won’t produce berries?” Mr. Z’s question helped students define the problem—the plant lacked a pollinator. He also prompted his students to ask questions: “Come up with a question whose answer will help you solve the problem better.” Students asked more about how pollination works and about the insect that pollinates the plant in its native Hawaii.

“Now that we understand the problem, I’d like you to use your imagination. Suppose you are an agricultural engineer. How do you think Mariana could solve her problem?” Encouraged to think “outside the box,” several students came up with ideas that Mr. Z had not thought of before. He reacted with excitement to each suggestion, reflecting each idea back to the class and asking questions so that he understood some of the more original or “crazy” ideas.

From all these ideas, students needed to plan the details of one solution. With guidance from Mr. Z, the students eventually recognized that Mariana could solve her problem with a hand pollinator that picked up pollen from one part of a flower and dropped it on another part. Mr. Z showed the students an array of materials that they

Instructional Strategies Snapshot 11.6: Engineering Design K–2

could use to create a hand pollinator, and they began to plan in small groups. Students could use the materials any way they wished, and the variety of objects they produced was very creative.

"Before we give Mariana your hand pollinators, what should we do to find out if they work? Any ideas?" With Mr. Z's guidance, the students developed a fair test of their pollinators using a model flower with baking soda to represent pollen.

As the students gained experience and saw how each other's pollinators worked, they got ideas for how to improve their pollinators. Mr. Z led a discussion about the importance of improving engineering designs and gave the children more time to see if they could get their pollinators to pick up and drop off more pollen.

Finally, Mr. Z led a discussion about how the children used five steps of an engineering process: ask questions, imagine solutions, plan, create, and improve the solutions to a problem. They also applied their knowledge of scientific ideas about what it takes for plants to produce fruit.

Source: Adapted from Engineering is Elementary 2011.

Grades 3–5

At the upper elementary grades, engineering design engages students in more formalized problem solving. Students define a problem using criteria for success and constraints or limits of possible solutions. Students research and consider multiple possible solutions to a given problem. Generating and testing solutions also becomes more rigorous as the students learn to optimize solutions by revising them several times to obtain the best possible design.

Instructional Strategies Snapshot 11.7: Engineering Design in Grades 3–5

Mrs. D's students had just returned from pulling weeds in their school vegetable garden. Some weeds were easy to remove while others had roots that were so deep or so wide that they were hard to remove. Mrs. D then showed students a picture of a giant redwood tree that fell over and whose roots were not exposed at the surface. "If the tree's roots were stronger, would it still be alive?" she asked the class. While humans can't design tree roots in real life, Mrs. D introduced an engineering design challenge that gave students insight into how a plant's **structure helps aid its function [CCC-6]**. The students worked in small groups in which they designed, tested, and improved a root system. Each group of students had a large cup, sand (or dirt), and several pipe cleaners for "roots."

The students discussed ideas for their design and then drew a model showing the structure of their root system. Then, the students constructed their root systems by twisting pipe cleaners together as shown in their drawing. Once the root system was made, students placed it into the cup and poured sand into the cup until the root system was buried. As the students worked, Mrs. D asked the groups about their design: What type of root system did you build? Why did you choose that design?

Students tested their root system by lightly pulling up on the roots. They noted on the paper with their drawing how well the root system worked (e.g., did the root come out with just one pull, a couple of pulls, or only with a very hard pull). The students discussed how they might improve their root-system design, drew a new model, and constructed a new root system. They tested their root system again, noting the results on the new drawing. Mrs. D asked the groups, "Which root system worked best?" and "Why do you think it worked better?"

After students had discussed the success or failure of their root systems and the reasons for the successes or failures in their groups, Mrs. D asked the groups to show the class their drawings along with the root system they constructed and explain why their design worked (or did not work). At the end of the discussion, Mrs. D reminded the students that scientists and engineers design, construct, and test their models many times to find the best solution to a problem.

Source: Adapted from Iridescent's Curiosity Machine 2015.
(https://www.cde.ca.gov/ci/sc/cf/ch11.asp#link22)

Grades 6–8

In the middle grades, students learn to sharpen the focus of problems by precisely specifying criteria and constraints of successful solutions. They take into account not only what needs the problem is intended to meet but also the larger context of the situation. This context allows them to recognize factors that limit certain solutions. Students can identify elements of different solutions and combine them to create new solutions. Students at this level are expected to use systematic methods to compare different solutions to see which best meet criteria and constraints and to test and revise solutions a number of times to arrive at an optimal design. Instruction at this level is illustrated with two short snapshots.

Instructional Strategies Snapshot 11.8: Engineering Design in Grades 6–8

During the “Girls Go Global” unit (McLeod 2014), pairs of girls designed and built a water carrier for a hypothetical user (a girl in a developing nation) with specific needs. As part of the testing process, they developed a survey to gather feedback about whether the carrier met the design constraints they identified. Another pair tested the carrier and completed the survey. Pairs redesigned and retested their carriers.

During another activity from the same unit, the girls built and tested biomass-burning stoves. They took the temperature of the water before and after their fuel burned and redesigned and retested the stoves to determine whether the redesign was more efficient (made the water hotter while using the same amount of fuel).

Grades 9–12

Engineering design at the high-school level engages students in complex problems that include issues of social and global significance. Such problems need to be broken down into simpler problems that can be tackled one at a time. Students are also expected to quantify criteria and constraints and use quantitative methods to compare the potential of different solutions. Emphasis is placed on identifying the best solution to a problem, which often involves researching how others have solved it before. Students are expected to use mathematics and/or computer simulations to test solutions under different conditions, prioritize criteria, consider trade-offs, and assess social and environmental impacts.

Instructional Strategies Snapshot 11.9: Global Engineering Design for High School

Global Systems Science (GSS) is a set of curriculum materials for high school teachers and students developed by the Lawrence Hall of Science. GSS is centered on critical societal issues of global concern, such as ecosystem change, losing biodiversity, climate change, and energy use, all of which require science for full understanding and thoughtful, intelligent engineering for solutions. For example, *Energy Use* (Erickson and Gould 2007) begins by inviting students to take an inventory of the ways that they use electricity. By "following the wires" back to a power plant and from there to a grid of all power plants in the country, students begin to grasp the vast infrastructure that supports our way of life.

Through laboratory experiments, students learned the basic principles on which electrical devices work, and through a brief history, they learned how our national energy policy came to be. They also learned about the huge amounts of fossil fuels burned for transportation, home heating, and industry on a daily basis and the small fraction of that energy that is actually put to use.

In the last portion of the unit, students conducted experiments and creative design activities to find ways to maintain our current standard of living while saving billions of dollars and reducing our impact on the environment (HS-ESS3-4, HS-LS2-7). The students also explored new technologies for satisfying the energy needs of a growing human population while keeping the impact of energy use to a minimum.

Resource

Full free access to GSS resources are provided in the following link:

https://www.cde.ca.gov/ci/sc/cf/ch11.asp#link23

Table 11.12 identifies different parts of a high school engineering design challenge called Lunar Plant Growth Chamber and categorizes them based on stages of the engineering design cycle. Free access to the Lunar Plant Growth Chamber by NASA is available at https://www.cde.ca.gov/ci/sc/cf/ch11.asp#link24.

Table 11.12. Stages of the Engineering Design Cycle for the NASA Plant Growth Challenge

Step of the Design Process	Students Actions
Step 1: Identify the Problem	Students should state the challenge problem in their own words. Example: How can I design a __________ that will __________?
Step 2: Identify Criteria and Constraints	Students should specify the design requirements (criteria). Example: Our growth chamber must have a growing surface of 10 square feet and have a delivery volume of 3 cubic feet or less. Students should list the limits on the design due to available resources and the environment (constraints). Example: Our growth chamber must be accessible to astronauts without leaving the spacecraft.
Step 3: Brainstorm Possible Solutions	Working in groups or as a whole class, students suggest ideas for aspects of the design and for the design as a whole. Each student in the group should sketch his or her own ideas as the group discusses ways to solve the problem. Labels and arrows should be included to identify parts and how they might move. These drawings should be quick and brief. Ideas are not critiqued, and multiple alternate ideas for problem solutions are accepted without making judgments or comparisons.
Step 4: Generate Ideas	Based on the collective results of the brainstorming session, each group outlines one or two designs for the solution with sketches that roughly describe both the whole system and the functioning of any critical parts.
Step 5: Explore Possibilities	The developed ideas should be shared and discussed among the team members and across teams. Students should record the pros, cons, and questions about each design idea directly on the paper next to the drawings. (This can be done with sticky notes.)

Table 11.12. Stages of the Engineering Design Cycle for the NASA Plant Growth Challenge *(continued)*

Step of the Design Process	Students Actions
Step 6: Select an Approach	Students should work in teams to identify a design that appears to solve the problem the best. This design may include elements from any of the preliminary designs, not only those developed by this team. In this step, each group should develop its chosen idea more thoroughly. For any object to be built, students should create new drawings that include multiple-plane views showing the design from the top, front, and one side as well as a three-dimensional depiction. These are to be drawn neatly, using rulers to draw straight lines and to make parts proportional. Parts and measurements should be clearly labeled. Detailed drawings for any critical sub-system (for example, water supply systems) are included. Students should write a statement that describes why they chose the solution. This should include some reference to the criteria and constraints identified above.
Step 7: Build a Model or Prototype	Students will construct a full-size or scale model based on their drawings. The teacher will help identify and acquire appropriate modeling materials and tools.
Step 8: Refine the Design	Students will examine and evaluate their prototypes or designs based on the criteria and constraints. Groups may enlist students from other groups to review the solution and help identify changes that need to be made. Based on criteria and constraints, teams must identify any problems and propose refinements or changes to their design as solutions.

Source: Adapted from NASA 2016

Teaching Science and Engineering Practices through Engineering

The engineering design cycle employs many of the science and engineering practices (SEPs) from the CA NGSS, but unique challenges crop up when applying the SEPs to engineering. Table 11.13 lists some common student difficulties and instructional strategies that teachers can use to help students overcome them (Crismond 2013). When planning lessons, teachers should be mindful of the specific SEPs being employed during each activity so that they can reinforce the appropriate student behaviors and ways of thinking. Teachers can also plan time at the end of lessons for students to reflect on how engaging in each practice deepened their understanding of that practice.

Table 11.13. What Teachers Can Do to Address Difficulties Students May Encounter as They Learn the Engineering Practices

SEP-1. Asking questions and defining problems. Reading and understanding instructions from the teacher about a design challenge is not the same as fully understanding the problem. Teachers need to remind students to avoid premature decisions about solutions until they fully grasp the problem and can describe the solution that is required.

SEP-2. Developing and using models. Beginning designers often sketch ideas that would not work in practice. Rapid prototyping, in which students build multiple models from simple materials, can often help students develop viable solutions. Students can also benefit from class discussions about the strengths and weaknesses of specific models since in both science and engineering models are only approximations of the actual phenomena or product being modeled.

SEP-3. Planning and carrying out investigations. The problems here are similar whether the purpose of an investigation is science or engineering. Students often change more than one variable at a time during testing, making the results difficult to interpret. It may be helpful to allow students to plan and conduct these flawed experiments so students can recognize the problem for themselves.

SEP-4. Analyzing and interpreting data. In science, analysis and interpretation of data may be the last step in a project to test a hypothesis, or it may suggest further tests that need to be made. In engineering, analysis and interpretation of data is also important but not the last step. Designing a solution based on the results of tests—called iteration—is a fundamental principle in engineering. It is important for students to observe and analyze the test carefully so they can improve the solution. Sometimes a series of questions can help students pay closer attention to the data. For example, the teacher might ask, “What did you observe during the test? What problem(s) did you notice? Why do you think that’s happening? How could you remedy the problem before the next test?”

SEP-5. Using mathematics and computational thinking. Students have difficulty transferring skills they learned solving abstract mathematical problems to concrete engineering solutions. Engineering provides additional opportunities to apply mathematics (such as maximizing the area enclosed by a fence) and computational thinking (such as varying parameters in a simulated solution) to concrete situations.

SEP-6. Designing solutions. Research shows that encouraging students to brainstorm more ideas to solve a problem results in better ideas. Encouraging students to generate many ideas before deciding on the best idea for developing a prototype to test will help your students avoid fixating on any one solution. Younger students benefit from the scaffolding of starting with a fixed prototype and varying from this default design.

Table 11.13. What Teachers Can Do to Address Difficulties Students May Encounter as They Learn the Engineering Practices *(continued)*

SEP-7. Engaging in argument from evidence. When teachers ask students to talk about different ideas for solving a problem, students tend to discuss just the supporting ideas for their favored solution. Teachers should encourage students to discuss the pros and cons of every solution. They should ask students to test ideas by measuring aspects of the design function and then use the evidence collected to decide which is better. Students can also develop a group process to judge and evaluate which solution best meets the criteria and constraints of the problem, combining both quantitative and qualitative features.
SEP-8. Obtaining, evaluating, and communicating information. Beginners sometimes confuse design with invention. Most engineers do not invent entirely new ideas to solve problems. They start by finding out how others have solved the problem. When faced with an engineering challenge, students should learn to first conduct research, which will involve obtaining, evaluating, and communicating information on the problem and alternative solutions. Their findings could be reported in many ways, such as providing a history of how certain products have evolved or developing a decision matrix to show how well different solutions match the criteria and constraints of the problem.

Source: Adapted from Crismond 2013.

The Pedagogy of Failure

Inventor and engineer Charles Kettering said, “Ninety-nine percent of success is built on failure.” Pedagogically, it is important for students to also document these “failures” and analyze them so that they can improve upon them later. Students should be encouraged to recognize that their initial designs, whether they “work” or not, are just the first stage of an iterative design cycle and can typically be improved with revision. Students succeed more when teachers cultivate a growth mindset where failure is an expected part of the everyday process.

Cognitively Guided Instruction

Cognitively Guided Instruction (CGI) is more commonly associated with mathematics instruction (Carpenter, Fennema, and Franke 1996; Carpenter 1999), but it may be used to develop students’ problem-solving abilities as they engage in engineering design. This instructional strategy calls for the teacher to ask students to think about different ways to solve a problem. The teacher differentiates instruction in response to students’ original ideas and guides each student according to his or her own developmental level and way of reasoning. After students generate strategies to solve a particular problem, students must explain their reasoning process in small groups, whole-class discussion, or as formal presentations.

Decision Matrices

In engineering, there is rarely a perfect solution. A decision matrix (also known as a Pugh Chart) is a thinking tool that helps students decide which solutions have the most advantages and the fewest disadvantages. The decision matrix itself is simply a table where every possible solution has its own column and every criterion or constraint has its own row. To construct the table, students define the problem that they wish to solve in terms of very specific criteria for success and constraints, or limits. Then, they research the problem and generate ideas for solutions. The decision matrix will help with the next step—deciding which idea best meets the criteria and constraints of the problem. Table 11.14 is an example decision matrix for selecting a new electricity source for a power plant in California (e.g., HS-ESS3-2). The decision matrix helps students organize their ideas and gets them to talk about why they value one solution over another.

Table 11.14. Decision Matrix for New Electricity Supply

Criteria	Max Value	Solar	Wind	Hydroelectric	Natural Gas	Coal
Carbon-free	5	5	5	5	1	1
Cheap ($ per MWh)	4	2 ($110)	3 ($58)	3 ($71)	4 ($15)	3 ($60)
Clean (no air pollution)	3	3	3	3	2	1
Consistent	3	1	1	3	3	3
Total	15	11	12	14	10	8

Constraints						
Available in California	Yes/No	Yes	Yes	Yes	Yes	Yes

Instructional Strategy Resources: Engineering

IEEE Institute of Electrical and Electronics Engineers. *Try Engineering.* https://www.cde.ca.gov/ci/sc/cf/ch11.asp#link25.

American Society for Engineering Education. *Teach Engineering, Curriculum for K12 Teachers.* https://www.cde.ca.gov/ci/sc/cf/ch11.asp#link26.

Instructional Strategies for Using Digital Technology

The field of science teaching and learning has been transformed by the increased availability and use of digital technology in the first part of the twenty-first century. Table 11.15 provides examples showing how technology brings new capabilities for measurement, data recording, data analysis, simulation, collaboration, and communication to each of the CA NGSS SEPs:

Table 11.15. How Digital Technology Transforms Instruction for Each Science and Engineering Practice

SEP-1. Asking questions and defining problems. Curiosity requires no technology, but technology allows students to share questions more easily through online discussions or question-voting systems (where students use online tools to vote on questions they want to address).

SEP-2. Developing and using models. Students can use tools such as NetLogo, StarLogo, spreadsheets, and others to develop computer models. Other software can make it easier to visually represent a conceptual model by, for example, creating a concept map. While hand-drawn models and diagrams are valuable, their digital counterparts are extremely easy to archive and revise. The ease of revision allows a shift from the initial model development to the process of progressive model refinement.

SEP-3. Planning and carrying out investigations. Simulations allow students to investigate processes at size and time scales that are not amenable to direct investigation in the classroom. Students can take virtual fieldtrips using Google Earth or collect measurements from satellite data. Technology has even transformed hands-on labs through tools such as probeware, which acquire real-time data that are more accurate than traditional analog methods.

SEP-4. Analyzing and interpreting data. Digital technology allows students to bring data together for collaborative analysis. For example, students can enter data into a collaborative online spreadsheet and compare their findings to classmates'. Computer tools also allow students to visualize and analyze vast quantities of digital data.

SEP-5. Using mathematics and computational thinking. Students can rapidly visualize their mathematical thinking by plotting data, adding trend lines, and calculating experimental error rapidly using spreadsheets and other tools. This allows teachers to shift the focus from the mechanics of mathematical thinking to its applications. Ultimately, the intuition developed from applying mathematics will motivate students when it comes time to build mathematical skills.

SEP-6. Constructing Explanations. Computer media allow students to more easily integrate a range of evidence into their explanations. They can insert photos, videos, and diagrams to illustrate different aspects of phenomena and their explanations.

SEP-6. Designing solutions. Computers allow for rapid prototyping as students create digital prototypes in computer modeling environments or using 3-D printers.

Table 11.15. How Digital Technology Transforms Instruction for Each Science and Engineering Practice *(continued)*

SEP-7. Engaging in argument from evidence. Communications technology allows for students to get more practice with argumentation. Online discussion tools allow students to engage in pair or small group discussions while still allowing a teacher to monitor all the classroom discussions (something not possible while circulating around a classroom in person).

SEP-8. Obtaining, evaluating, and communicating information. Technology enhances all aspects of information sharing, including student-student, teacher-student, student-teacher, and student-scientist. Students can use a full range of new media to communicate their solutions, including video, presentations, infographics, and interactive Web sites. The Internet also provides students access to previous solutions to problems, and students need digital literacy skills to find and evaluate this flood of information. Twenty-first century communication tools are inherently participatory, meaning that students are more likely to be engaged in posting comments that evaluate information than simply being producers or consumers of media.

Instructional Strategy Resources: Technology in the Classroom

Herr, Norm 2015. *Collaborative Data Analysis in the Science Classroom*
https://www.cde.ca.gov/ci/sc/cf/ch11.asp#link27.
An online professional development program for using technology to help teachers pool data in their classroom.

NASA Airborne Science Program
https://www.cde.ca.gov/ci/sc/cf/ch11.asp#link28
NASA scientists in Antarctica and the Arctic interact with students in the classroom via the Internet.

Instructional Strategies for Supporting Language Demands in Science

One of the major shifts for the CA NGSS is that students engage more in "doing" science, but engaging in each of the SEPs is a language-rich experience requiring more speaking and listening, reading, and writing. Supporting students to develop and use general academic language and to speak and write with the precision demanded by science thinking is an essential part of supporting science learning.

The *NRC Framework* identifies several ways in which science communication differs from other genres:

- *Science and engineering communications are "multimodal"* (they use an interconnected mix of words, diagrams, graphs, and mathematics). For example, the definition of a word might be found only as a label in a diagram, or text that refers to a graph does not make sense unless the reader also examines and understands the graph itself.
- *Science and engineering frequently use unfamiliar and specialized words* ("jargon"). Some of these words are labels for multi-stage processes (like *mitosis* or *fission*) or otherwise communicate large amounts of information.
- *In science and engineering, the details matter.* Students therefore need to pay constant attention to every word when obtaining scientific or engineering information. The process is sometimes complicated by a mismatch between the level of importance an idea has within the grammatical structure of a sentence and its importance for the scientific meaning of a sentence. For example, short introductory phrases and prepositions can have a dramatic impact on the scientific meaning of a sentence (e.g., "assuming a frictionless surface"). Students must learn to read differently in order to notice all these pieces (CA CCSSM MP.6, CA CCSS for ELA/Literacy RI.3.4).

Promoting a Climate of Scientific Discourse

Teachers can begin cultivating a learning environment that welcomes respectful discussion of ideas. Students' comments must be valued for their contribution to the thinking even when expressed incompletely or with flaws in the language usage. Ensuring participation of all students, whatever the language level of each, is critical to supporting science learning for all.

Academic Language

In the science classroom every student is learning new academic language. Attention to issues of language development, while critical for the students who are English learners, is also important for those whose primary language is English. The *English Language Arts/English Language Development Framework for California Public School Kindergarten Through Grade Twelve (CA ELA/ELD Framework)* provides comprehensive guidelines to build students' proficiency in language and literacy across all the academic disciplines and through K–12, with particular attention to the needs of ELs. That document also outlines the key goal of integrating ELD instruction throughout the day and across all disciplines. Science teachers therefore become important teachers of language alongside their content. This work begins with a few simple steps:

- Routinely examining the texts and tasks used for instruction in order to identify language that could be challenging for ELs
- Determining where there are opportunities to highlight and discuss particular language resources (e.g., powerful or precise vocabulary, different ways of combining ideas in sentences, ways of starting paragraphs to emphasize key ideas)
- Adjusting whole-group instruction or work with small groups or individuals to provide adequate and appropriate support

Science class should not, however, be a vocabulary class. Teachers need to decide which words might be challenging for ELs and require focused support, which are essential for conveying scientific meaning, and which can be replaced with more familiar words. Table 11.16 displays a system to categorize words based on how often they are used in everyday and discipline-specific contexts (Beck, McKeown, and Kucan 2002, 15–30; 2013). Teachers can use these categories to decide how much time to spend on explicitly defining the words and when the most appropriate time is to introduce them. Domain-specific words are often labels for fundamental ideas within science and can be essential for conveying meaning. Teachers and texts should explicitly introduce these words and work with students to come up with appropriate definitions. In other cases, the domain-specific jargon really is not necessary, and it may be more worthwhile to replace a domain-specific word with parallels from everyday language (i.e., "thermophilic bacteria" become "heat-loving bacteria"). This approach does not constitute "dumbing down" science, as the NRC (2000) emphasizes that "knowing vocabulary does not necessarily help students develop or understand explanations" (NRC 2000, 133). Rather, research from university-level students shows that replacing jargon with everyday language improves conceptual understanding and does not have adverse effects in more advanced courses that rely on specialized vocabulary (Schoerning 2014; Li et al. 2014). The main point is that teachers need to consider how to address each vocabulary word on a case-by-case basis.

Table 11.16. Categories of Vocabulary

VOCABULARY	DEFINITION	EXAMPLES
Conversational (Tier One)	Words of everyday use	*happy, dog, run, family, boy, play, water*
General Academic (Tier Two)	Words that are far more likely to appear in text than in everyday use, are highly generalizable because they appear in many types of texts, and often represent precise or nuanced meanings of relatively common things	*develop, technique, disrupt, fortunate, frightening, enormous, startling* *strolled, essential*
Domain-Specific (Tier Three)	Words that are specific to a domain or field of study and key to understanding a new concept	*equation, place value, germ, improvisation, tempo, percussion, landform, thermometer*

Source: Bringing Words to Life: Robust Vocabulary Instruction. Beck, McKeown, and Kucan 2013. Copyright Guilford Press. Reprinted with permission of The Guilford Press.

Integration with the Common Core

The CA CCSS for ELA/Literacy place an increased emphasis on developing literacy in reading, writing, speaking, and listening for technical subjects, including science. These standards are not requirements to simply read *about* science and do not replace it. They prepare students to *do* science and *learn* science concepts. Elementary teachers that teach multiple subjects can design lessons that support both science learning and literacy development at the same time. Secondary teachers require cross-disciplinary discussion and collaboration.

Teachers can begin by noticing the synergy between the SEPs in the CA NGSS and CA CCSS for ELA/Literacy (table 11.17). Students will develop science language, reading, and writing skills through their engagement in science practices. The practice of doing science often motivates language development because it introduces a need for communication. As students develop a model, they use diagrams but also words to label features that are important. As they present their ideas to their classmates in small groups, they find they must express the ideas precisely so that others can understand what they are thinking. As students develop the language to express their thoughts more clearly, they in turn refine their science thinking.

Table 11.17. Overlaps Between NGSS Practices and CA CCSS ELA/Literacy

NGSS PRACTICE	CA CCSS FOR ELA/LITERACY
SEP-3: Planning and Carrying out Investigations	• Following Complex Processes and Procedures • Conducting Research
SEP-6: Constructing Explanations and Designing Solutions	• Using Textual Evidence and Attending to Detail • Synthesizing Complex Information • Explaining Concepts, Processes and Procedures
SEP-7: Engaging in Argument from Evidence	• Making Arguments • Assessing Arguments
SEP-8: Obtaining, Evaluating, and Communicating Information	• Conducting Research • Gathering Relevant Evidence • Translating Information from One Form to Another

Source: Adapted from Pimentel 2013.

Both CA NGSS and CA CCSS place an emphasis on classroom discourse. While science class is not focused on formal language instruction, it is a venue for students to learn and practice grade-appropriate argumentation skills. Students should also understand and reflect on why these skills are necessary to make their observations and arguments clear to others. Teachers make instructional choices about the tasks that students undertake and must explicitly provide students opportunities for classroom discourse that includes speaking and listening as well as analyzing written arguments and producing their own. These tasks support science learning and language and literacy development at the same time.

Several additional resources provide guidance on the relationship between CA CCSS for ELA/Literacy and the CA NGSS. Appendix M of the CA NGSS focuses on grades six through twelve. The Council of Chief State School Officers (2012) analyzes the language demands in NGSS and suggests appropriate support for English learners so that they can access the grade-level content while building language proficiency.

Instructional Strategy Resources: Language Demands

Understanding Language
https://www.cde.ca.gov/ci/sc/cf/ch11.asp#link29.
Provides resources and research to help develop educator awareness of the critical role language plans in the CA CCSS and the CA NGSS and demonstrate ways in which EL proficiency and disciplinary knowledge can be developed simultaneously in the context of content instruction.

Integrating ELD Standards into K–12 Mathematics and Science Teaching and Learning: A Supplementary Resource for Educators
https://www.cde.ca.gov/ci/sc/cf/ch11.asp#link30.
A supplemental resource, when used with the standards and content frameworks, illustrates ways to integrate the use of ELD standards into science curriculum design and instruction.

Instructional Strategies for Integrating Mathematical Practices into the CA NGSS

Science and mathematics teachers are jointly responsible for bridging the gap between mathematics as learned in the mathematics classroom and its applications in the science classroom. This begins by recognizing the synergy in learning goals between the mathematical practices (MP) in the California Common Core State Standards for Mathematics (CA CCSSM) and the CA NGSS.

To ensure the CA NGSS goal of a coherent curriculum, science teachers need to know what level of mathematics their students have mastered and what they are currently learning so that they can have students apply these skills to science. Science teachers can also provide math teachers relevant examples. Appendix L of the CA NGSS indicates when key ideas useful to science are first introduced in the CA CCSSM and provides specific examples where science and math overlap at each grade level.

Transferring math skills to science applications, however, requires explicit attention to differences between the disciplines. For example, both science and math have practices using the word “argument” but use the term very differently. Successful mathematical arguments can be pure reasoning and logic, but science arguments always require specific evidence. This difference is so pronounced that the CA NGSS connection boxes never provide a link to CA CCSSM MP.3: Make viable arguments.

Both science and math also rely heavily on ratios and functional relationships, but students need to take the numeric interpretation from math and learn how to add the richer set of meanings that these relationships have in science. A ratio of distance over time in science, for example, introduces an entirely new concept: speed, which is different from either distance or time. Scientists attach physical significance to these new quantities and reason directly with them (e.g., they interpret the quantity of speed in terms of how far something travels and how long it takes to get there). The mathematics teacher may begin this process by introducing units and relationships of quantities (such as length and area), while the science teacher provides contexts in which students can go beyond manipulating the ratios to the level where students develop meaning from these relationships. This level of understanding is the ultimate goal of both the CA CCSS and the CA NGSS.

Instructional Strategy Resources: Integrating Mathematical Practices

Illustrative Mathematics
(https://www.cde.ca.gov/ci/sc/cf/ch11.asp#link31)
Twenty-five lessons that focus on science and represent many grade levels from grade two to high school.

National Council of Teachers of Mathematics (NCTM)
(https://www.cde.ca.gov/ci/sc/cf/ch11.asp#link32)
Illuminations is a companion site to NCTM and lists several mathematics lessons for different grade levels that focus on science.

NASA Space Math
(https://www.cde.ca.gov/ci/sc/cf/ch11.asp#link33)
Compendium of activities that use mathematics to enhance understanding of space science. Also see Earth Math (https://www.cde.ca.gov/ci/sc/cf/ch11.asp#link34) and the other NASA booklets in that series.

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