Appendix D

NGSS Summary: Three Dimensions and Scientific/Engineering Practices

**Part 1: Introduction to the *Next Generation Science Standards***

The *Next Generation Science Standards* (NGSS) is the standards document for science education (NGSS Lead States, 2013). Its standards – or “performance expectations” – represent what students in grades K-12 should know and be able to do with respect to science and engineering (NGSS Lead States, 2013). Each performance expectation draws from three “dimensions” (or parts) within the NGSS: 1) Scientific and Engineering Practices, 2) Crosscutting Concepts, and 3) Disciplinary Core Ideas (Figure 1).

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  |  | **Performance Expectations** |  |  |
|  |  |  |  |  |
| Science & Engineering Practices |  | Crosscutting Concepts |  | Disciplinary Core Ideas |

**Figure 1*.*** Performance Expectations reference three dimensions of the NGSS (NGSS Lead States, 2013).

***Scientific and Engineering Practices***. These are the core skills and activities of scientists and engineers, and will be the focus of our NGSS attention in this course (Table 1). Note that for two of the practices (1 and 6), there is a difference between scientific and engineering practices; otherwise, scientists and engineers engage in similar practices.

**Table 1.** Scientific and Engineering Practices in the NGSS (NGSS Lead States, 2013).

|  |  |  |
| --- | --- | --- |
| **#** | **Scientific Practices** | **Engineering Practices** |
| 1 | Asking Questions | Defining Problems |
| 2 | Developing and Using models |
| 3 | Planning and Carrying out Investigations |
| 4 | Analyzing and Interpreting data |
| 5 | Using Mathematics and Computational Thinking |
| 6 | Constructing Explanations | Designing Solutions |
| 7 | Engaging in Argument from Evidence |
| 8 | Obtaining, Evaluating, and Communicating Information |

Aside from these skills and activities, the NGSS includes *what* it is that scientists and engineers should know. This content is captured in the next two dimensions: the crosscutting concepts and disciplinary core ideas. These crosscutting concepts and disciplinary core ideas included in the NGSS do not represent *every* idea that is known in science and engineering! Rather, those who worked to develop the standards chose for their importance, relevance and applicability.

***Crosscutting Concepts***. Crosscutting concepts are “big ideas” that apply to all fields of science and engineering (e.g., patterns are important to chemists, physicists, geologists, biologists, environmental scientists, and engineers) (Table 2).

**Table 2.** Crosscutting Concepts (NGSS Lead States, 2013).

|  |
| --- |
| 1. Patterns
 |
| 1. Cause and effect: Mechanism and explanation
 |
| 1. Scale, proportion, quantity
 |
| 1. Systems and system models
 |
| 1. Energy and matter: Flows, cycles, and conservation
 |
| 1. Structure and function
 |
| 1. Stability and change
 |

***Disciplinary Core Ideas*.** Core content ideas are discipline-specific ideas (Table 3). They identify what students should know in each content area: physical science; life science; Earth and space science; and engineering, technology and applications of science.

**Table 3.** Disciplinary Core Ideas (NGSS Lead States, 2013).

|  |
| --- |
| *Physical Sciences* |
| PS1: Matter and its interactions |
| PS2: Motion and stability: Forces and interactions |
| PS3: Energy |
| PS4: Waves and their applications in technologies for information transfer |
| *Life Sciences* |
| LS1: From molecules to organisms: Structures and processes |
| LS2: Ecosystems: Interactions, energy and dynamics |
| LS3: Heredity: Inheritance and variation of traits |
| LS4: Biological evolution: Unity and diversity |
| *Earth & Space Sciences* |
| ESS1: Earth’s place in the universe |
| ESS2: Earth’s systems |
| ESS3: Earth and human activity |
| *Engineering, Technology & Applications of Science* |
| ETS1: Engineering design |
| ETS2: Links among engineering, technology, science and society |

**Part 2: Introduction to Practices**

The term, “practices,” has been used in multiple documents, including in the Common Core State Standards for Mathematics (NGAC & CCSSO, 2010) and the NGSS (Achieve, Inc., 2013). Let’s pause for a moment to think about why the word “practice” is used instead of other words like skills, processes, or actions. The authors of the text, *Ready, Set, Science*, Michaels, Shouse, and Schweingruber, shared:

Science practice involves doing something and learning something in such a way that the doing and learning cannot really be separated. Thus, “practice” … encompasses several of the different dictionary definitions of the term. It refers to doing something repeatedly in order to become proficient (as in practicing the trumpet). It refers to learning something so thoroughly that it becomes second nature (as practicing thrift). And it refers to using one’s knowledge to meet an objective (as in practicing law or practicing teaching). (2008, p. 34)

In this class, you will be gradually introduced to the “Scientific and Engineering Practices” within the NGSS as they apply to different lessons that you teach. Different types of scientific investigations or engineering challenges emphasize different practices. Given that elementary students should be conducting many investigations and engineering design challenges throughout a school year, students will likely be engaged in each of the practices multiple times by the time they depart for summer vacation.

In what follows, we provide summaries of the following practices:

* Practice 1 - Asking Questions (for Science)
* Practice 2 – Developing and Using Models
* Practice 3 – Planning and Carrying Out Investigations
* Practice 4 – Analyzing and Interpreting Data
* Practice 5 – Mathematical and Computational Reasoning
* Practice 6 – Constructing Explanations (for Science)
* Practice 7 – Engaging in Argument from Evidence
* Practice 8 – Obtaining, Evaluating and Communicating Information
* Practice 1 – Defining Problems (for Engineering)
* Practice 6 – Designing Solutions (for Engineering)

Each practice is presented in two parts: 1) how scientists engage in the practice, and 2) how elementary students engage in the practice. We have likely oversimplified the practices in this document. Nearly all of the practices (perhaps with the exception of Practice 6 - Constructing Explanations) are relevant to both science *and* engineering. However, to reduce text and simplify your learning about the practices, we have presented most of the “Scientific and Engineering” practices in the context of what *scientists* do and how elementary students engage in science, omitting language like “engineers also ask questions” (for Practice 1) or “models are also utilized in engineering” (for Practice 2).

**Part 3: Practice Summaries**

***Practice 1: Asking Questions (for Science)***

*How Scientists and Engineers Engage in this Practice:*

Scientists tend to ask the following kinds of questions: “What exists and what happens? Why does it happen? How does one know?” (NRC, 2012, p. 54). Scientists ask more specific questions related to their areas. For example, they might ask: What is the relationship between hurricane frequency and climate change? or What are the potentially harmful effects of Bisphenol A, a common ingredient in some plastics, on human health?

In addition to these large, overriding questions that focus and guide scientists’ work, scientists ask multiple questions as they go about being scientists! They ask questions, e.g.: of one another, about scientific journal articles, about the data that they and others collect, and about how such data may be analyzed, interpreted, or communicated.

*How Elementary Students Engage in this Practice:*

Questions guide elementary science investigations, whether the students or the teacher/ curriculum create(s) those questions. Examples include: What does an earthworm eat? Where does the sun rise and set? How can we use a wire, battery, and bulb to light a bulb? or What is the relationship between the force applied to an object and the resulting motion of the object?

In addition, students should be encouraged to ask many questions as they engage in the entire science learning process. The authors of the *Framework* articulate this well: “Students at any grade level should be able to ask questions of each other about the texts they read, the features of the phenomena they observe, and the conclusions they draw from their models of scientific investigations” (NRC, 2012, p. 55).

***Practice 2: Developing and Using Models***

*How Scientists Engage in this Practice:*

Scientists use representational models to illustrate and explore their ideas about scientific phenomena. These models are externalized, meaning that they capable of being shared with other people in usually a written or drawn form. Models include: *2-D drawings[[1]](#footnote-1)* (e.g., of force diagrams), *3-D physical representations* (e.g., of molecules); *equations* (e.g., the ideal gas law which describes the relationship between pressure, temperature, and volume of ideal gases in closed containers); and *computer simulations* (e.g., of the effects of CO2 on agriculture throughout the world).

It is important to note that representational models represent one or more aspect(s) of a scientific phenomenon, and are not exactly like the real phenomenon. Also, as scientists learn new information about the phenomenon, they revise their models.

*How Elementary Students Engage in this Practice:*

Developing models: Elementary students can generate their own models of phenomena, which are usually represented by labeled drawings. For example, students might: illustrate their understanding of a concept (e.g., the water cycle within a closed container); then investigate the phenomenon; and then revise their model according to their investigation.

Using models: Elementary students often use models such as drawings, computer animations, or physical objects. For example, students might learn how to represent a force on an object using an arrow or may examine physical models of the solar system to help them get a sense of relative diameters of the planets. As students get into upper-elementary and middle level grades, they may use other kinds of models like equations and computer simulations.

***Practice 3: Planning and Carrying Out Investigations***

*How Scientists Engage in this Practice:*

Scientists plan and carry out investigations: “(1) to systematically describe the world and (2) to develop and test theories and explanations of how the world works” (NRC, 2012, p. 59). Investigations that are planned and carried out may take many forms, including:

Observation (field-based research): Scientists make observations to describe the world, carefully documenting what they observe. For example, geologists have documented the layers within core samples of sedimentary rock found at Sideling Hill in Western Maryland.

Experiment (“bench” or laboratory science): Scientists plan and carry out experiments that involve altering one variable (the *independent* variable) to determine if there is a change in another variable (the *dependent* variable). In their planning, scientists must make many decisions, including: what needs to be carefully controlled, how to measure variables with accuracy and precision, how many trials to conduct, and sources of error that may impact the results.

Theoretical Research: Some scientists plan and carry out *theoretical* investigations, often using computer programs and simulations to model the world and explain phenomena. For example, some theoretical astrophysicists have computer simulations to test their ideas about how the universe formed and to model the rate of expansion of the universe.

*How Elementary Students Engage in this Practice:*

Planning Investigations: In today’s elementary classrooms, when children do science, they often carry out investigations that teachers/curricula have planned for them. However, children can: consider how they might plan investigations, help plan simple investigations, and – given the appropriate amount of time – plan investigations themselves. Even kindergarteners who want to know what worms eat can contribute ideas about how to investigate this question.

Carrying Out Investigations: Elementary children frequently conduct experiments (e.g., by altering one variable to see how it affects another variable) and make observations (inside and outside of the classroom). Students can also postulate ideas about the world as a theoretical scientist might.

***Practice 4: Analyzing and Interpreting Data***

*How Scientists Engage in this Practice:*

Scientists organize the data that they collect so that they can analyze and interpret the data. Data can be numerical (or quantitative) in form, or can be observational and descriptive (qualitative) in nature. Tables and graphs – on paper, computer or other digital device – can be used to help with the organization, analysis, and interpretation of data. For example, scientists from around the world have gathered data about the migratory patterns of Monarch butterflies. These large data sets must be organized and analyzed to make sense of them.

*How Elementary Students Engage in this Practice:*

The emphasis of this practice for elementary children is on using words, drawings, or numbers to carefully record observations in an organized way to be able to compare, contrast, and make sense of patterns. Students can be encouraged to use tables, graphs or drawings to represent numeric and non-numeric data. Examples of data that elementary students might analyze and interpret include: measurements of how far a car travels after leaving a ramp (numerical data), whether or not an item sinks or floats (categorical data), and direct observations of the life cycle stages of a butterfly (observational data). Computers and other digital devices should be used to organize and represent data when available and accessible to students.

***Practice 5: Using Mathematics and Computational Thinking***

*How Scientists Engage in this Practice:*

Mathematics and computation are essential tools in science. Mathematics involves counting, measuring, basic operations (addition, subtraction, multiplication, division), statistics, geometry, algebra and beyond. Computation involves the development and use of computer programs and simulations. Together, these tools allow, for example: variables to be measured and analyzed, computer programs to be made to simulate real phenomena; predictions about phenomena to be made and tested, and the quantitative results of experiments to be determined significant (or not).

*How Elementary Students Engage in this Practice:*

Elementary students can engage in this practice when mathematical skills and concepts are both relevant to the scientific investigation and appropriate given students’ mathematical abilities. Young children may use basic skills like counting or relative measurement (e.g., determining how far something traveled in “blocks” instead of inches). As students gain mathematical experience, they can use basic operations (e.g., to determine how far an object traveled by adding two legs of the trip together) and graphing techniques.

***Practice 6: Constructing Explanations (for Science)***

*How Scientists Engage in this Practice:*

When a scientist investigates a scientific phenomenon, the scientist typically - as a first step - describes the phenomenon in detail. But the investigation does not end with a description of what occurred. The next step is to understand *why* the scientific phenomenon occurred. The scientist answers this “why” question by constructing a scientific explanation.

Scientists construct scientific explanations by (a) identifying the theories and concepts that underlie a particular phenomenon, and then (b) applying the theories/concepts to that phenomenon.[[2]](#footnote-2) In this manner the scientist clarifies why the phenomenon occurred.

For example, meteorologists and other scientists have made the evidence-based argument that global temperatures have increased. When asked *why* this has occurred, many scientists have explained this increase as a result of increases in greenhouse gases by humans.

*How Elementary Students Engage in this Practice:*

When elementary students attempt to answer the question, “Why?” in science, they are engaged in constructing an explanation. These explanations take the following form: *[this event/phenomenon] happened because [application of science concepts].*

For example, a fifth-grade student may be asked: Why do both light bulbs dim when a bulb is added to a simple circuit already containing a bulb? The student may explain:

Explanation: Both bulbs become dimmer when the second bulb is added because the total amount of resistance in the circuit has increased. An increase in resistance causes a decrease in current, and a decrease in current causes a decrease in bulb brightness.

Note that this explanation is connected to core ideas in electricity (in this case, about the relationship between resistance and current).[[3]](#footnote-3)

***Practice 7: Engaging in Argument from Evidence***

*How Scientists Engage in this Practice:*

Scientific arguments consist of a claim, evidence (data), and reasons. In this sense, a claim can be regarded as a statement that the scientist considers to be true. Whenever a scientist makes a claim, other scientists will carefully review that claim – together with all of its supporting evidence - to determine whether the claim is valid. This process helps ensure that scientific claims are as accurate as possible. Therefore, in terms of basic scientific practices, scientists must be able to (a) make evidence-based arguments to support their own scientific claims,[[4]](#footnote-4) and (b) critically analyze the claims and evidence of other scientists.

*How Elementary Students Engage in this Practice:*

Elementary students engage in argument from evidence anytime they make a claim (e.g., a statement that they regard to be true) and provide evidence and reasoning to support that claim.

For example, a class of elementary students is trying to decide whether an “empty” cup is really empty. To do this, students make observations of clear plastic cups that are turned upside down and pushed under water. After the observations are complete, a student argues:

*Claim*: The “empty” cup is not really empty. There is actually air inside the cup.

*Evidence-based reasoning:* I think that there is air in the cup because the upside-down cup did not completely fill with water when it was pushed under water (*the evidence*). The air that was caught in the upside-down cup stopped all of the water from coming in (*the reason*).

Engaging in argument from evidence also includes occasions when students provide reasons why they agree or disagree with another student’s claim.

***Practice 8: Obtaining, Evaluating and Communicating Information***

*How Scientists Engage in this Practice:*

Scientists must be able to comprehend what they read (e.g., in textbooks and scientific journals) or hear/see (e.g., in other forms of media like Internet videos or audio newscasts) about science. They must do so as critical consumers, determining the credibility of what they read/hear/see. It is equally important for lay citizens (i.e., nonscientists) to be critical consumers of science!

Scientists must also be able to communicate well, both in verbal and written form. Such communication occurs in the following formal and informal venues: “peer-reviewed journals, books, conference presentations, and carefully constructed websites … discussions, email messages, phone calls, and blogs” (NRC, 2012, p. 75). As readers and writers, scientists must know how to use and interpret not only words, but also tables, diagrams, graphs, and mathematical equations.

*How Elementary Students Engage in this Practice:*

Obtaining Information: Elementary students may obtain information in multiple ways (e.g., by reading, watching videos, listening to the teacher or their peers). However, the emphasis of this practice is on when students obtain information by reading grade-level appropriate science texts or watching/listening to “other reliable media” (Achieve, Inc., 2013, p. 15 Appendix F). Here “other reliable media” may include watching videos (e.g., *Planet Earth*).

Evaluating Information: Elementary students can evaluate what they read about science by: examining the evidence the author(s) use to make claims in the text, and by comparing what they know (e.g., from class investigations) to the claims in the text.

Communicating Information: Elementary students communicate information by:

* Sharing their ideas verbally in group and class discussions;
* Writing and drawing their observations and ideas (e.g., predictions, models, and explanations);
* Writing reports that utilize information from scientific texts/media; and
* Engaging in more formal opportunities to present their work (e.g., on posters).

***Practice 1: Defining Problems (for Engineering)***

*How Engineers Engage in this Practice:*

Engineers are problem-solvers, and the world is full of problems that engineers can solve. For example, engineers are working to solve the following problems:

* troops wounded by improvised explosive devices (IEDs)
* pesticides that not only kill pests, but harm other insects that are important pollinators; and
* transportation systems that depend upon fossil fuels.

Engineers have the following kinds of goals to solve these problems, e.g., to create:

* better armor for troops to protect them from IEDs;
* safer pesticides or alternatives to pesticides; and
* more energy efficient transportation systems.

Engineers ask questions about the problems that they are trying to solve, including: What are the constraints? What are the criteria? and What do I need to know (e.g., about science or people) to solve this problem? Constraints are limitations such as available: budget, materials, and time. Criteria help engineers evaluate and compare possible solutions. Criteria include absolute requirements (e.g., must weigh less than a certain amount), as well as criteria that can be met to greater or lesser extents (e.g., must weight as little as possible).

*How Elementary Students Engage in this Practice:*

Meeting this practice in elementary school means that students should be given opportunities to define a problem “that can be solved through the development of an object, tool, process, or system” (Achieve, Inc., 2013, p. 4 Appendix F). Older elementary students should be able to not only define this problem, but also specify the constraints (materials, time, cost) and criteria for success. No matter the age, students should be given opportunities to envision – through drawings or written descriptions or rudimentary models (e.g., play dough) – what the designed solution might look like; however, the emphasis here is on students defining the problem, not on implementing a solution.

For example, a young child may define the following problem: “I want to be able to pick up an insect to look at it up close, but I do not want to have to touch the bug.” She might envision – through drawings – a tool that could be built to solve this problem. An older elementary student who suggests the same problem would consider possible constraints (e.g., less than $2.00 to make) and criteria (e.g., must not harm the insect).

***Practice 6: Designing Solutions (for Engineering)***

*How Engineers Engage in this Practice:*

Engineers design solutions to problems. These solutions are often called “designs,” “designed solutions,” or “technologies”. In any case, the solutions might be products (i.e., physical things) or processes (i.e., steps regarding how to make or do something). There are usually multiple solutions that are capable of solving a problem; there is no one single correct answer. Determining the best solution depends on how well the solution meets criteria. Those criteria often compete with one another (e.g., low cost may be preferred, but the best material is high cost).

Engineers use “the engineering design process” to generate solutions. There are many different forms of the engineering design process used by professional engineers. Nearly all of these engineering design processes include the following activities:

* Defining and researching the problem, goal, constraints, and criteria.
* Brainstorming multiple possible solutions to solve the problem.
* Comparing those brainstormed solutions based upon criteria.
* Selecting one solution[[5]](#footnote-5) and making a detailed plan about how to create it; this plan is typically drawn and includes a materials list.
* Creating the solution (often done by technicians, rather than engineers).
* Testing the solution.
* Determining how the solution can be improved.
* Developing a new and improved solution using the above steps (repeat as necessary).

The engineering design process steps are typically depicted as a cycle rather than a list, representing the iterative nature of engineering design. For example, engineers improve their design solutions multiple times (not just once), and sometimes go back and re-investigate the problem before making subsequent improvements.

*How Elementary Students Engage in this Practice:*

Elementary children design solutions by using a simple **engineering design process** (EDP) e.g. We will use the Engineering is Elementary (EiE) EDP. There are five steps to this process as shown in Table 4. See Figure 2 for a cyclical representation of the EiE EDP.

**Table 4.** EiE Engineering Design Process (EiE, 2019).

|  |  |
| --- | --- |
| **EiE EDP Step** | **Activities** |
| Ask | * Defining and researching the problem, goal, constraints, and criteria.
 |
| Imagine | * Brainstorming multiple possible solutions to solve the problem.
* Comparing those brainstormed solutions based upon criteria.
 |
| Plan | * Selecting one solution.
* Making a detailed plan about how to create it.
* Including a list of needed materials.
 |
| Create | * Creating the solution.
* Testing the solution.
 |
| Improve | * Determining how the solution can be improved.
* Developing a new and improved solution using the above steps (repeat as necessary).
 |



**Figure 2**. The EiE EDP depicted as an iterative cycle (EiE, 2019).

1. Note that not all drawings represent models. Models may be drawn, but importantly must serve to represent some aspect(s) of a scientific phenomenon. [↑](#footnote-ref-1)
2. The word “theory” as it is used by scientists is very different from the word “theory” as it is used in everyday conversation (e.g., “I have a theory about that…”) Scientific theories are *not* simple guesses. They are well-respected scientific ideas based on significant evidence that has been collected for years across many different scientific contexts. [↑](#footnote-ref-2)
3. In the *Framework*, the term, “explanation” has a very specific meaning that is embodied by Practice 6. This is different than the many occasions in which you may be asked to “explain” your answer to a question. When you are asked to “explain your answer” this is a very general way of signaling that you need to provide detail and reasoning to justify your response. Also, “explanation” within Practice 6 is different than the “explain” section in the 5E lesson plan. The explain section in 5E has a broader informal meaning, referring to the process by which the student answers the focus question. [↑](#footnote-ref-3)
4. These are not “arguments” in the everyday sense of people getting upset with one another over disagreements. An argument in science is a well-reasoned claim backed by evidence. [↑](#footnote-ref-4)
5. We use the general term, “solution,” here. For some engineers, the solution is a prototype (physical model). For others, it is a computer program or simulation. [↑](#footnote-ref-5)