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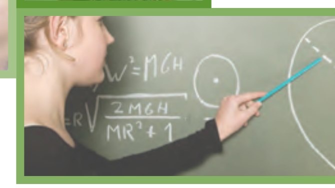

Dimension 1
SCIENTIFIC AND ENGINEERING PRACTICES

From its inception, one of the principal goals of science education has been to cultivate students' scientific habits of mind, develop their capability to engage in scientific inquiry, and teach them how to reason in a scientific context [1, 2]. There has always been a tension, however, between the emphasis that should be placed on developing knowledge of the content of science and the emphasis placed on scientific practices. A narrow focus on content alone has the unfortunate consequence of leaving students with naive conceptions of the nature of scientific inquiry [3] and the impression that science is simply a body of isolated facts [4].

This chapter stresses the importance of developing students' knowledge of how science and engineering achieve their ends while also strengthening their competency with related practices. As previously noted, we use the term "practices," instead of a term such as "skills," to stress that engaging in scientific inquiry requires coordination both of knowledge and skill simultaneously.

In the chapter's three major sections, we first articulate why the learning of science and engineering practices is important for K-12 students and why these practices should reflect those of professional scientists and engineers. Second, we describe in detail eight practices we consider essential for learning science and engineering in grades K-12 (see Box 3-1). Finally, we conclude that acquiring skills in these practices supports a better understanding of how scientific knowledge is produced and how engineering solutions are developed. Such understanding will help students become more critical consumers of scientific information.

BOX 3-1

PRACTICES FOR K-12 SCIENCE CLASSROOMS

1. Asking questions (for science) and defining problems (for engineering)
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 (for science) and designing solutions (for engineering)
7. Engaging in argument from evidence
8. Obtaining, evaluating, and communicating information

Throughout the discussion, we consider practices both of science and engineering. In many cases, the practices in the two fields are similar enough that they can be discussed together. In other cases, however, they are considered separately.

WHY PRACTICES?

Engaging in the practices of science helps students understand how scientific knowledge develops; such direct involvement gives them an appreciation of the wide range of approaches that are used to investigate, model, and explain the world. Engaging in the practices of engineering likewise helps students understand the work of engineers, as well as the links between engineering and science. Participation in these practices also helps students form an understanding of the crosscutting concepts and disciplinary ideas of science and engineering; moreover, it makes students' knowledge more meaningful and embeds it more deeply into their worldview.

The actual doing of science or engineering can also pique students' curiosity, capture their interest, and motivate their continued study; the insights thus gained help them recognize that the work of scientists and engineers is a creative

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endeavor [5, 6]—one that has deeply affected the world they live in. Students may then recognize that science and engineering can contribute to meeting many of the major challenges that confront society today, such as generating sufficient energy, preventing and treating disease, maintaining supplies of fresh water and food, and addressing climate change. Any education that focuses predominantly on the detailed products of scientific labor—the facts of science—without developing an understanding of how those facts were established or that ignores the many important applications of science in the world misrepresents science and marginalizes the importance of engineering.

Understanding How Scientists Work

The idea of science as a set of practices has emerged from the work of historians, philosophers, psychologists, and sociologists over the past 60 years. This work illuminates how science is actually done, both in the short term (e.g., studies of activity in a particular laboratory or program) and historically (studies of laboratory notebooks, published texts, eyewitness accounts) [7-9]. Seeing science as a set of practices shows that theory development, reasoning, and testing are components of a larger ensemble of activities that includes networks of participants and institutions [10, 11], specialized ways of talking and writing [12], the development of models to represent systems or phenomena [13-15], the making of predictive inferences, construction of appropriate instrumentation, and testing of hypotheses by experiment or observation [16].

Our view is that this perspective is an improvement over previous approaches in several ways. First, it minimizes the tendency to reduce scientific practice to a single set of procedures, such as identifying and controlling variables, classifying entities, and identifying sources of error. This tendency overemphasizes experimental investigation at the expense of other practices, such as modeling, critique, and communication. In addition, when such procedures are taught in isolation from science content, they become the aims of instruction in and of themselves rather than a means of developing a deeper understanding of the concepts and purposes of science [17].

Second, a focus on practices (in the plural) avoids the mistaken impression that there is one distinctive approach common to all science—a single "scientific method"—or that uncertainty is a universal attribute of science. In reality, practicing scientists employ a broad spectrum of methods, and although science involves many areas of uncertainty as knowledge is developed, there are now many aspects of scientific knowledge that are so well established as to be unquestioned foundations of the culture and its technologies. It is only through engagement in the practices that students can recognize how such knowledge comes about and why some parts of scientific theory are more firmly established than others.

Third, attempts to develop the idea that science should be taught through a process of inquiry have been hampered by the lack of a commonly accepted definition of its constituent elements. Such ambiguity results in widely divergent pedagogic objectives [18]—an outcome that is counterproductive to the goal of common standards.

The focus here is on important practices, such as modeling, developing explanations, and engaging in critique and evaluation (argumentation), that have too often been underemphasized in the context of science education. In particular, we stress that critique is an essential element both for building new knowledge in general and for the learning of science in particular [19, 20]. Traditionally, K-12 science education has paid little attention to the role of critique in science. However, as all ideas in science are evaluated against alternative explanations and compared with evidence, acceptance of an explanation is ultimately an assessment of what data are reliable and relevant and a decision about which explanation is the most satisfactory. Thus knowing why the wrong answer is wrong can help secure a deeper and stronger understanding of why the right answer is right. Engaging in argumentation from evidence about an explanation supports students' understanding of the reasons and empirical evidence for that explanation, demonstrating that science is a body of knowledge rooted in evidence.

How the Practices Are Integrated into Both Inquiry and Design

One helpful way of understanding the practices of scientists and engineers is to frame them as work that is done in three spheres of activity, as shown in Figure 3-1. In one sphere, the dominant activity is investigation and empirical inquiry. In the second, the essence of work is the construction of explanations or designs using reasoning, creative thinking, and models. And in the third sphere, the ideas, such as the fit of models and explanations to evidence or the appropriateness of product designs, are analyzed, debated, and evaluated [21-23]. In all three spheres

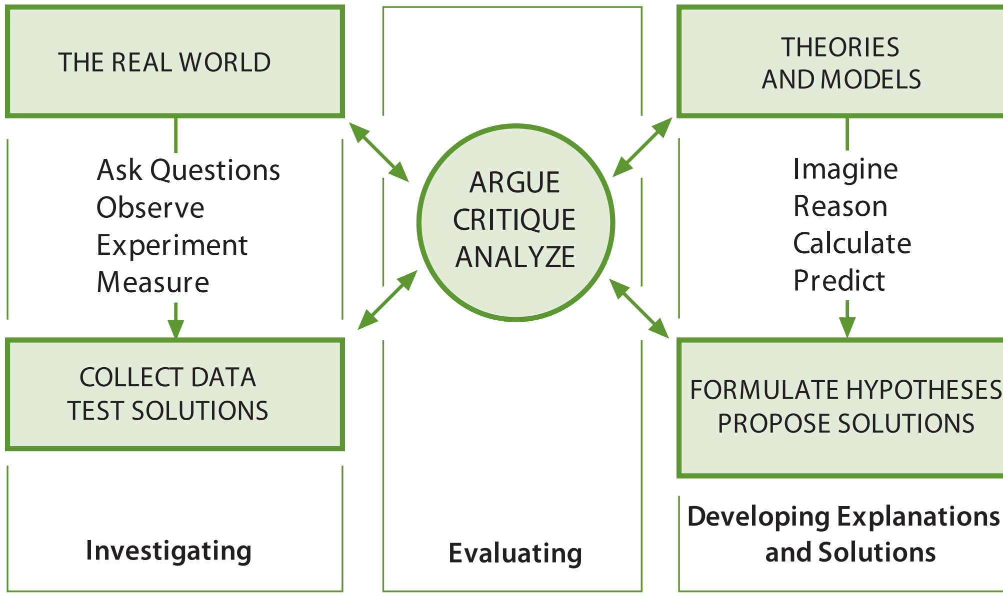

FIGURE 3-1 The three spheres of activity for scientists and engineers.

of activity, scientists and engineers try to use the best available tools to support the task at hand, which today means that modern computational technology is integral to virtually all aspects of their work.

At the left of the figure are activities related to empirical investigation. In this sphere of activity, scientists determine what needs to be measured; observe phenomena; plan experiments, programs of observation, and methods of data collection; build instruments; engage in disciplined fieldwork; and identify sources of uncertainty. For their part, engineers engage in testing that will contribute data for informing proposed designs. A civil engineer, for example, cannot design a new highway without measuring the terrain and collecting data about the nature of the soil and water flows.

The activities related to developing explanations and solutions are shown at the right of the figure. For scientists, their work in this sphere of activity is to draw from established theories and models and to propose extensions to theory or create new models. Often, they develop a model or hypothesis that leads to new questions to investigate or alternative explanations to consider. For engineers, the major practice is the production of designs. Design development also involves constructing models, for example, computer simulations of new structures or processes that may be used to test a design under a range of simulated conditions or, at a later stage, to test a physical prototype. Both scientists and engineers use their models—including sketches, diagrams, mathematical relationships, simulations, and physical models—to make predictions about the likely behavior of a system, and they then collect data to evaluate the predictions and possibly revise the models as a result.

Between and within these two spheres of activity is the practice of evaluation, represented by the middle space. Here is an iterative process that repeats at every step of the work. Critical thinking is required, whether in developing and refining an idea (an explanation or a design) or in conducting an investigation. The dominant activities in this sphere are argumentation and critique, which often lead to further experiments and observations or to changes in proposed models, explanations, or designs. Scientists and engineers use evidence-based argumentation to make the case for their ideas, whether involving new theories or designs, novel ways of collecting data, or interpretations of evidence. They and their peers then attempt to identify weaknesses and limitations in the argument, with the ultimate goal of refining and improving the explanation or design.

In reality, scientists and engineers move, fluidly and iteratively, back and forth among these three spheres of activity, and they conduct activities that might involve two or even all three of the modes at once. The function of Figure 3-1 is therefore solely to offer a scheme that helps identify the function, significance, range, and diversity of practices embedded in the work of scientists and engineers. Although admittedly a simplification, the figure does identify three overarching categories of practices and shows how they interact.

How Engineering and Science Differ

Engineering and science are similar in that both involve creative processes, and neither uses just one method. And just as scientific investigation has been defined in different ways, engineering design has been described in various ways. However, there is widespread agreement on the broad outlines of the engineering design process [24, 25].

Like scientific investigations, engineering design is both iterative and systematic. It is iterative in that each new version of the design is tested and then modified, based on what has been learned up to that point. It is systematic in that a number of characteristic steps must be undertaken. One step is identifying the problem and defining specifications and constraints. Another step is generating ideas for how to solve the problem; engineers often use research and group

sessions (e.g., "brainstorming") to come up with a range of solutions and design alternatives for further development. Yet another step is the testing of potential solutions through the building and testing of physical or mathematical models and prototypes, all of which provide valuable data that cannot be obtained in any other way. With data in hand, the engineer can analyze how well the various solutions meet the given specifications and constraints and then evaluate what is needed to improve the leading design or devise a better one.

In contrast, scientific studies may or may not be driven by any immediate practical application. On one hand, certain kinds of scientific research, such as that which led to Pasteur's fundamental contributions to the germ theory of disease, were undertaken for practical purposes and resulted in important new technologies, including vaccination for anthrax and rabies and the pasteurization of milk to prevent spoilage. On the other hand, many scientific studies, such as the search for the planets orbiting distant stars, are driven by curiosity and undertaken with the aim of answering a question about the world or understanding an

Students' opportunities to immerse themselves in these practices and to explore why they are central to science and engineering are critical to appreciating the skill of the expert and the nature of his or her enterprise.

observed pattern. For science, developing such an explanation constitutes success in and of itself, regardless of whether it has an immediate practical application; the goal of science is to develop a set of coherent and mutually consistent theoretical descriptions of the world that can provide explanations over a wide range of phenomena, For engineering, however, success is measured by the extent to which a human need or want has been addressed.

Both scientists and engineers engage in argumentation, but they do so with different goals. In engineering, the goal of argumentation is to evaluate prospective designs and then produce the most effective design for meeting the specifications and constraints. This optimization process typically involves trade-offs between competing goals, with the consequence that there is never just one "correct" solution to a design challenge. Instead, there are a number of possible solutions, and choosing among them inevitably involves personal as well as technical and cost considerations. Moreover, the continual arrival of new technologies enables new solutions.

In contrast, theories in science must meet a very different set of criteria, such as parsimony (a preference for simpler solutions) and explanatory coherence (essentially how well any new theory provides explanations of phenomena that fit with observations and allow predictions or inferences about the past to be made). Moreover, the aim of science is to find a single coherent and comprehensive theory for a range of related phenomena. Multiple competing explanations are regarded as unsatisfactory and, if possible, the contradictions they contain must be resolved through more data, which enable either the selection of the best available explanation or the development of a new and more comprehensive theory for the phenomena in question.

Although we do not expect K-12 students to be able to develop new scientific theories, we do expect that they can develop theory-based models and argue using them, in conjunction with evidence from observations, to develop explanations. Indeed, developing evidence-based models, arguments, and explanations is key to both developing and demonstrating understanding of an accepted scientific viewpoint.

A focus on practices (in the plural) avoids the mistaken impression that there is one distinctive approach common to all science—a single "scientific method."

PRACTICES FOR K-12 CLASSROOMS

The K-12 practices described in this chapter are derived from those that scientists and engineers actually engage in as part of their work. We recognize that students cannot reach the level of competence of professional scientists and engineers, any more than a novice violinist is expected to attain the abilities of a virtuoso. Yet students' opportunities to immerse themselves in these practices and to explore why they are central to science and engineering are critical to appreciating the skill of the expert and the nature of his or her enterprise.

We consider eight practices to be essential elements of the K-12 science and engineering curriculum:

1. Asking questions (for science) and defining problems (for engineering)
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 (for science) and designing solutions (for engineering)
7. Engaging in argument from evidence
8. Obtaining, evaluating, and communicating information

In the eight subsections that follow, we address in turn each of these eight practices in some depth. Each discussion describes the practice, articulates the major competencies that students should have by the end of 12th grade ("Goals"), and sketches how their competence levels might progress across the preceding grades ("Progression"). These sketches are based on the committee's judgment, as there is very little research evidence as yet on the developmental trajectory of each of these practices. The overall objective is that students develop both the facility and the inclination to call on these practices, separately or in combination, as needed to support their learning and to demonstrate their understanding of science and engineering. Box 3-2 briefly contrasts the role of each practice's manifestation in science with its counterpart in engineering. In doing science or engineering, the practices are used iteratively and in combination; they should not be seen as a linear sequence of steps to be taken in the order presented.

BOX 3-2

DISTINGUISHING PRACTICES IN SCIENCE FROM THOSE IN ENGINEERING

1. Asking Questions and Defining Problems

Science begins with a question about a phenomenon, such as "Why is the sky blue?" or "What causes cancer?," and seeks to develop theories that can provide explanatory answers to such questions. A basic practice of the scientist is formulating empirically answerable questions about phenomena, establishing what is already known, and determining what questions have yet to be satisfactorily answered.

Engineering begins with a problem, need, or desire that suggests an engineering problem that needs to be solved. A societal problem such as reducing the nation's dependence on fossil fuels may engender a variety of engineering problems, such as designing more efficient transportation systems, or alternative power generation devices such as improved solar cells. Engineers ask questions to define the engineering problem, determine criteria for a successful solution, and identify constraints.

2. Developing and Using Models

Science often involves the construction and use of a wide variety of models and simulations to help develop explanations about natural phenomena. Models make it possible to go beyond observables and imagine a world not yet seen. Models enable predictions of the form "if . . . then . . . therefore" to be made in order to test hypothetical explanations.

Engineering makes use of models and simulations to analyze existing systems so as to see where flaws might occur or to test possible solutions to a new problem. Engineers also call on models of various sorts to test proposed systems and to recognize the strengths and limitations of their designs.

3. Planning and Carrying Out Investigations

Scientific investigation may be conducted in the field or the laboratory. A major practice of scientists is planning and carrying out a systematic investigation, which requires the identification of what is to be recorded and, if applicable, what are to be treated as the dependent and independent variables (control of variables). Observations and data collected from such work are used to test existing theories and explanations or to revise and develop new ones.

Engineers use investigation both to gain data essential for specifying design criteria or parameters and to test their designs. Like scientists, engineers must identify relevant variables, decide how they will be measured, and collect data for analysis. Their investigations help them to identify how effective, efficient, and durable their designs may be under a range of conditions.

4. Analyzing and Interpreting Data

Scientific investigations produce data that must be analyzed in order to derive meaning. Because data usually do not speak for themselves, scientists use a range of tools—including tabulation, graphical interpretation, visualization, and statistical analysis—to identify the significant features and patterns in the data. Sources of error are identified and the degree of certainty calculated. Modern technology makes the collection of large data sets much easier, thus providing many secondary sources for analysis.

Engineers analyze data collected in the tests of their designs and investigations; this allows them to compare different solutions and determine how well each one meets specific design criteria—that is, which design best solves the problem within the given constraints. Like scientists, engineers require a range of tools to identify the major patterns and interpret the results.

5. Using Mathematics and Computational Thinking

In **science,** mathematics and computation are fundamental tools for representing physical variables and their relationships. They are used for a range of tasks, such as constructing simulations, statistically analyzing data, and recognizing, expressing, and applying quantitative relationships. Mathematical and computational approaches enable predictions of the behavior of physical systems, along with the testing of such predictions. Moreover, statistical techniques are invaluable for assessing the significance of patterns or correlations.

In **engineering,** mathematical and computational representations of established relationships and principles are an integral part of design. For example, structural engineers create mathematically based analyses of designs to calculate whether they can stand up to the expected stresses of use and if they can be completed within acceptable budgets. Moreover, simulations of designs provide an effective test bed for the development of designs and their improvement.

BOX 3-2 continued

DISTINGUISHING PRACTICES IN SCIENCE FROM THOSE IN ENGINEERING

6. Constructing Explanations and Designing Solutions

The goal of **science** is the construction of theories that can provide explanatory accounts of features of the world. A theory becomes accepted when it has been shown to be superior to other explanations in the breadth of phenomena it accounts for and in its explanatory coherence and parsimony. Scientific explanations are explicit applications of theory to a specific situation or phenomenon, perhaps with the intermediary of a theory-based model for the system under study. The goal for students is to construct logically coherent explanations of phenomena that incorporate their current understanding of science, or a model that represents it, and are consistent with the available evidence.

Engineering design, a systematic process for solving engineering problems, is based on scientific knowledge and models of the material world. Each proposed solution results from a process of balancing competing criteria of desired functions, technological feasibility, cost, safety, esthetics, and compliance with legal requirements. There is usually no single best solution but rather a range of solutions. Which one is the optimal choice depends on the criteria used for making evaluations.

7. Engaging in Argument from Evidence

In **science,** reasoning and argument are essential for identifying the strengths and weaknesses of a line of reasoning and for finding the best explanation for a natural phenomenon. Scientists must defend their explanations, formulate evidence based on a solid foundation of data, examine their own understanding in light of the evidence and comments offered by others, and collaborate with peers in searching for the best explanation for the phenomenon being investigated.

In **engineering,** reasoning and argument are essential for finding the best possible solution to a problem. Engineers collaborate with their peers throughout the design process, with a critical stage being the selection of the most promising solution among a field of competing ideas. Engineers use systematic methods to compare alternatives, formulate evidence based on test data, make arguments from evidence to defend their conclusions, evaluate critically the ideas of others, and revise their designs in order to achieve the best solution to the problem at hand.

8. Obtaining, Evaluating, and Communicating Information

Science cannot advance if scientists are unable to communicate their findings clearly and persuasively or to learn about the findings of others. A major practice of science is thus the communication of ideas and the results of inquiry—orally, in writing, with the use of tables, diagrams, graphs, and equations, and by engaging in extended discussions with scientific peers. Science requires the ability to derive meaning from scientific texts (such as papers, the Internet, symposia, and lectures), to evaluate the scientific validity of the information thus acquired, and to integrate that information.

Engineers cannot produce new or improved technologies if the advantages of their designs are not communicated clearly and persuasively. Engineers need to be able to express their ideas, orally and in writing, with the use of tables, graphs, drawings, or models and by engaging in extended discussions with peers. Moreover, as with scientists, they need to be able to derive meaning from colleagues' texts, evaluate the information, and apply it usefully. In engineering and science alike, new technologies are now routinely available that extend the possibilities for collaboration and communication.