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GUIDING ASSUMPTIONS AND ORGANIZATION OF THE FRAMEWORK

The conceptual framework presented in this report is based on a large and growing body of research on teaching and learning science. Much of this research base has been synthesized in other National Research Council (NRC) reports. Research on how children learn science and the implications for science instruction in grades K-8 was central to *Taking Science to School* [1], *America's Lab Report* [2] examined the role of laboratory experiences in high school science instruction, and *Learning Science in Informal Environments* [3] focused on the role of science learning experiences outside school. Complementing these publications, *Systems for State Science Assessment* [4] studied large-scale assessments of science learning, and *Engineering in K-12 Education* [5] looked into the knowledge and skills needed to introduce students to engineering in grades K-12. All of these NRC reports have been essential input to the development of the framework.

The framework also builds on two other prior works on standards: *Benchmarks for Science Literacy* published by the American Association for the Advancement of Science (AAAS) [6] and the NRC's *National Science Education Standards* (*NSES*) [7]. In addition, the committee examined more recent efforts, including the *Science Framework for the 2009 National Assessment of Educational Progress* [8], *Science College Board Standards for College Success* [9], the National Science Teachers Association's (NSTA's) Science Anchors project [10], and a variety of state and international science standards and curriculum specifications.

PRINCIPLES OF THE FRAMEWORK

Several guiding principles, drawn from what is known about the nature of learning science, underlie both the structure and the content of the framework. These principles include young children's capacity to learn science, a focus on core ideas, the development of true understanding over time, the consideration both of knowledge and practice, the linkage of science education to students' interests and experiences, and the promotion of equity.

Children Are Born Investigators

The research summarized in *Taking Science to School* [1] revealed that children entering kindergarten have surprisingly sophisticated ways of thinking about the world, based in part on their direct experiences with the physical environment, such as watching objects fall or collide and observing plants and animals [11-16]. They also learn about the world through everyday activities, such as talking with their families, pursuing hobbies, watching television, and playing with friends [3]. As children try to understand and influence the world around them, they develop ideas about their role in that world and how it works [17-19]. In fact, the capacity of young children—from all backgrounds and socioeconomic levels—to reason in sophisticated ways is much greater than has long been assumed [1]. Although they may lack deep knowledge and extensive experience, they often engage in a wide range of subtle and complex reasoning about the world [20-23]. Thus, before they even enter school, children have developed their own ideas about the physical, biological, and social worlds and how they work. By listening to and taking these ideas seriously, educators can build on what children already know and can do. Such initial ideas may be more or less cohesive and sometimes may be incorrect. However, some of children's early intuitions about the world can be used as a foundation to build remarkable understanding, even in the earliest grades. Indeed, both building on and refining prior conceptions (which can include misconceptions) are important in teaching science at any grade level. The implication of these findings for the framework is that building progressively more sophisticated explanations of natural phenomena is central throughout grades K-5, as opposed to focusing only on description in the early grades and leaving explanation to the later grades. Similarly, students can engage in scientific and engineering practices beginning in the early grades.

Focusing on Core Ideas and Practices

The framework focuses on a limited set of core ideas in order to avoid the coverage of multiple disconnected topics—the oft-mentioned mile wide and inch deep. This focus allows for deep exploration of important concepts, as well as time for students to develop meaningful understanding, to actually practice science and engineering, and to reflect on their nature. It also results in a science education that extends in a more coherent way across grades K-12.

The core ideas also can provide an organizational structure for the acquisition of new knowledge. Understanding the core ideas and engaging in the scientific and engineering practices helps to prepare students for broader understanding, and deeper levels of scientific and engineering investigation, later on—in high school, college, and beyond. One rationale for organizing content around core ideas comes from studies comparing experts and novices in any field. Experts understand the core principles and theoretical constructs of their field, and they use them to make sense of new information or tackle novel problems. Novices, in contrast, tend to hold disconnected and even contradictory bits of knowledge as isolated facts and struggle to find a way to organize and integrate them [24]. The assumption, then, is that helping students learn the core ideas through engaging in scientific and engineering practices will enable them to become less like novices and more like experts.

Importantly, this approach will also help students build the capacity to develop more flexible and coherent—that is, wide-ranging—understanding of science. Research on learning shows that supporting development of this kind of understanding is challenging, but it is aided by explicit instructional support that stresses connections across different activities and learning experiences.

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Understanding Develops Over Time

To develop a thorough understanding of scientific explanations of the world, students need sustained opportunities to work with and develop the underlying ideas and to appreciate those ideas' interconnections over a period of years rather than weeks or months [1]. This sense of development has been conceptualized in the idea of learning progressions [1, 25, 26]. If mastery of a core idea in a science discipline is the ultimate educational destination, then well-designed learning progressions provide a map of the routes that can be taken to reach that destination. Such progressions describe both how students' understanding of the idea matures over time and the instructional supports and experiences that are needed for them to make progress. Learning progressions may extend all the way from preschool to 12th grade and beyond—indeed, people can continue learning about scientific core ideas their entire lives. Because learning progressions extend over multiple years, they can prompt educators to consider how topics are presented at each grade level so that they build on prior understanding and can support increasingly sophisticated learning. Hence, core ideas and their related learning progressions are key organizing principles for the design of the framework.

Science and Engineering Require Both Knowledge and Practice

Science is not just a body of knowledge that reflects current understanding of the world; it is also a set of practices used to establish, extend, and refine that knowledge. Both elements—knowledge and practice—are essential.

In science, knowledge, based on evidence from many investigations, is integrated into highly developed and well-tested theories that can explain bodies of data and predict outcomes of further investigations. Although the practices used to develop scientific theories (as well as the form that those theories take) differ from one domain of science to another, all sciences share certain common features at the core of their inquiry-based and problem-solving approaches. Chief among these features is a commitment to data and evidence as the foundation for developing claims. The argumentation and analysis that relate evidence and theory are also essential features of science; scientists need to be able to examine, review, and evaluate their own knowledge and ideas and critique those of others. Argumentation and analysis include appraisal of data quality, modeling of theories, development of new testable questions from those models, and modification of theories and models as evidence indicates they are needed.

Finally, science is fundamentally a social enterprise, and scientific knowledge advances through collaboration and in the context of a social system with well-developed norms. Individual scientists may do much of their work independently or they may collaborate closely with colleagues. Thus, new ideas can be the product of one mind or many working together. However, the theories, models, instruments, and methods for collecting and displaying data, as well as the norms for building arguments from evidence, are developed collectively in a vast network of scientists working together over extended periods. As they carry out their research, scientists talk frequently with their colleagues, both formally and informally. They exchange emails, engage in discussions at conferences, share research techniques and analytical procedures, and present and respond to ideas via publication in journals and books. In short, scientists constitute a community whose members work together to build a body of evidence and devise and test theories. In addition, this community and its culture exist in the larger social and economic context of their place and time and are influenced by events, needs, and norms from outside science, as well as by the interests and desires of scientists.

Similarly, engineering involves both knowledge and a set of practices. The major goal of engineering is to solve problems that arise from a specific human need or desire. To do this, engineers rely on their knowledge of science and mathematics as well as their understanding of the engineering design process. Defining and solving the problem, that is, specifying what is needed and designing a solution for it, are the parts of engineering on which we focus in this framework, both because they provide students a place to practice the application of their understanding of science and because the design process is an important way for K-12 students to develop an understanding of engineering as

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a discipline and as a possible career path. The work of engineers, like the work of scientists, involves both individual and cooperative effort; and it requires specialized knowledge. Hence, we include both engineering practices and engineering core ideas in this framework.

Connecting to Students' Interests and Experiences

A rich science education has the potential to capture students' sense of wonder about the world and to spark their desire to continue learning about science throughout their lives. Research suggests that personal interest, experience, and enthusiasm—critical to children's learning of science at school or in other settings—may also be linked to later educational and career choices [27-30]. Thus, in order for students to develop a sustained attraction to science and for them to appreciate the many ways in which it is pertinent to their daily lives, classroom learning experiences in science need to connect with their own interests and experiences.

As a strategy for building on prior interest, the disciplinary core ideas identified here are described not only with an eye toward the knowledge that students bring with them to school but also toward the kinds of questions they are likely to pose themselves at different ages. Such questions as "Where do we come from?," "Why is the sky blue?," and "What is the smallest piece of matter?" are fundamental hooks that engage young people. Framing a curriculum around such sets of questions helps to communicate relevance and salience to this audience.

Promoting Equity

Equity in science education requires that all students are provided with equitable opportunities to learn science and become engaged in science and engineering practices; with access to quality space, equipment, and teachers to support and motivate that learning and engagement; and adequate time spent on science. In addition, the issue of connecting to students' interests and experiences is particularly important for broadening participation in science. There is increasing recognition that the diverse customs and orientations that members of different cultural communities bring both to formal and to informal science learning contexts are assets on which to build—both for the benefit of the student and ultimately of science itself. For example, researchers have documented that children reared in rural agricultural communities, who experience intense and regular interactions with plants and animals, develop more sophisticated understanding of ecology and biological species than do urban and suburban children of the same age [31-33].

Others have identified connections between children's culturally based storytelling and their engagement in argumentation and science inquiry, and some of these researchers have also documented pedagogical means of using such connections to support students' science learning and promote educational equity [34]. The research demonstrates the importance of embracing diversity as a means of enhancing learning about science and the world, especially as society in the United States becomes progressively more diverse with respect to language, ethnicity, and race.

The goal of educational equity is one of the reasons to have rigorous standards that apply to all students. Not only should all students be expected to attain these standards, but also work is needed to ensure that all are provided with high-quality opportunities to engage in significant science and engineering learning.

STRUCTURE OF THE FRAMEWORK

Based on the guiding principles outlined above, we have created a framework—comprised of three dimensions—that broadly outlines the knowledge and practices of the sciences and engineering that all students should learn by the end of high school:

- Dimension 1 describes scientific and engineering practices.
- Dimension 2 describes crosscutting concepts—that is, those having applicability across science disciplines.
- Dimension 3 describes core ideas in the science disciplines and of the relationships among science, engineering, and technology.

The three dimensions of the framework, which constitute the major conclusions of this report, are presented in separate chapters. However, in order to facilitate students' learning, the dimensions must be woven together in standards, curricula, instruction, and assessments. When they explore particular disciplinary ideas from Dimension 3, students will do so by engaging in practices articulated in Dimension 1 and should be helped to make connections to the crosscutting concepts in Dimension 2.

Dimension 1: Practices

Dimension 1 describes (a) the major practices that scientists employ as they investigate and build models and theories about the world and (b) a key set of engineering practices that engineers use as they design and build systems. We use the term "practices" instead of a term such as "skills" to emphasize that engaging in scientific investigation requires not only skill but also knowledge that is specific to each practice.

Similarly, because the term "inquiry," extensively referred to in previous standards documents, has been interpreted over time in many different ways throughout the science education community, part of our intent in articulating the practices in Dimension 1 is to better specify what is meant by inquiry in science and the range of cognitive, social, and physical practices that it requires. As in all inquiry-based approaches to science teaching, our expectation is that students will themselves engage in the practices and not merely learn about them secondhand. Students cannot comprehend scientific practices, nor fully appreciate the nature of scientific knowledge itself, without directly experiencing those practices for themselves.

Dimension 2: Crosscutting Concepts

The crosscutting concepts have application across all domains of science. As such, they provide one way of linking across the domains in Dimension 3. These crosscutting concepts are not unique to this report. They echo many of the unifying concepts and processes in the *National Science Education Standards* [7], the common themes in the *Benchmarks for Science Literacy* [6], and the unifying concepts in the *Science College Board Standards for College Success* [9]. The framework's structure also reflects discussions related to the NSTA Science Anchors project, which emphasized the need to consider not only disciplinary content but also the ideas and practices that cut across the science disciplines.

Dimension 3: Disciplinary Core Ideas

The continuing expansion of scientific knowledge makes it impossible to teach all the ideas related to a given discipline in exhaustive detail during the K-12 years.

But given the cornucopia of information available today virtually at a touch—people live, after all, in an information age—an important role of science education is not to teach "all the facts" but rather to prepare students with sufficient core knowledge so that they can later acquire additional information on their own. An education focused on a limited set of ideas and practices in science and engineering should enable students to evaluate and select reliable sources of scientific information and allow them to continue their development well beyond their K-12 school years as science learners, users of scientific knowledge, and perhaps also as producers of such knowledge.

With these ends in mind, the committee developed its small set of core ideas in science and engineering by applying the criteria listed below. Although not every core idea will satisfy every one of the criteria, to be regarded as core, each idea must meet at least two of them (though preferably three or all four).

Specifically, a core idea for K-12 science instruction should

1. Have broad importance across multiple sciences or engineering disciplines or be a key organizing principle of a single discipline.
2. Provide a key tool for understanding or investigating more complex ideas and solving problems.
3. Relate to the interests and life experiences of students or be connected to societal or personal concerns that require scientific or technological knowledge.
4. Be teachable and learnable over multiple grades at increasing levels of depth and sophistication. That is, the idea can be made accessible to younger students but is broad enough to sustain continued investigation over years.

In organizing Dimension 3, we grouped disciplinary ideas into four major domains: the physical sciences; the life sciences; the earth and space sciences; and engineering, technology, and applications of science. At the same time, true to Dimension 2, we acknowledge the multiple connections among domains. Indeed, more and more frequently, scientists work in interdisciplinary teams that blur traditional boundaries. As a consequence, in some instances core ideas, or elements of core ideas, appear in several disciplines (e.g., energy, human impact on the planet).

Each core idea and its components are introduced with a question designed to show some aspect of the world that this idea helps to explain. The question

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is followed by a description of the understanding about the idea that should be developed by the end of high school. This structure is intended to stress that posing questions about the world and seeking to answer them is fundamental to doing science.

The inclusion of core ideas related to engineering, technology, and applications of science reflects an increasing emphasis at the national level on considering connections among science, technology, engineering, and mathematics. It is also informed by a recent report from the NRC on engineering education in K-12, which highlights the linkages—which go both ways—between learning science and learning engineering. Just as new science enables or sometimes demands new technologies, new technologies enable new scientific investigations, allowing scientists to probe realms and handle quantities of data previously inaccessible to them.

Moreover, the line between applied science and engineering is fuzzy. It is impossible to do engineering today without applying science in the process, and, in many areas of science, designing and building new experiments requires scientists to engage in some engineering practices. This interplay of science and engineering makes it appropriate to place engineering and technology as part of the science framework at the K-12 level. In this way, students can better see how science and engineering pertain to real-world problems and explore opportunities to apply their scientific knowledge to engineering design problems once this linkage is made.

Finally, our effort to identify a *small* number of core ideas may disappoint some scientists and educators who find little or nothing of their favorite science topics included in the framework. But the committee is convinced that by building a strong base of core knowledge and competencies, understood in sufficient depth to be used, students will leave school better grounded in scientific knowledge and practices—and with greater interest in further learning in science—than when instruction "covers" multiple disconnected pieces of information that are memorized and soon forgotten once the test is over.

Progressions Across K-12

The framework emphasizes developing students' proficiency in science in a coherent way across grades K-12 following the logic of learning progressions. Developing detailed learning progressions for all of the practices, concepts, and ideas that make up the three dimensions was beyond the committee's charge; however, we do provide some guidance on how students' facility with the practices, concepts, and ideas may develop over multiple grades. For the practices and crosscutting concepts, the committee developed sketches of the possible progression for each practice or concept. These progressions do not specify grade bands because there was not enough available evidence to do so.

For the disciplinary core ideas, we provide a set of grade band endpoints for each component idea that describe the developing understanding that students should have acquired by the ends of grades 2, 5, 8, and 12, respectively. These endpoints indicate how this idea should be developed across the span of the K-12 years. In standards, curriculum, and instruction, a more complete sequence that integrates the core ideas with the practices and crosscutting concepts will be needed.

When possible, the grade band endpoints were informed by research on teaching and learning, particularly on learning progressions (see Appendix B for a list of the references the committee consulted). The committee referred to this literature to help determine students' capabilities at a particular grade band given appropriate instructional support as well as potential difficulties. However, the availability of such research is uneven across the core and component ideas of Dimension 3. For this reason, the endpoints were also informed by the committee's judgment about grade appropriateness. All in all, the endpoints provide a set of initial hypotheses about the progression of learning that can inform standards and serve as a basis for additional research.

The endpoints follow a common trend across the grades. In grades K-2, we choose ideas about phenomena that students can directly experience and investigate. In grades 3-5, we include invisible but chiefly still macroscopic entities, such as what is inside the body or Earth, with which children will have had little direct experience. When microscopic entities are introduced, no stress is placed on understanding their size—just that they are too small to see directly. However, pictures, physical models, and simulations can represent the entities and relate them to phenomena that the students can investigate and interpret. In grades 6-8, we move to atomic-level explanations of physical phenomena and cellular-level explanations of life processes and biological structures, but without detail on the inner workings of an atom or a cell. Finally, in grades 9-12 we shift to subatomic and subcellular explanations. A similar progression of scales and abstraction of models applies in addressing phenomena of large scales and deep time. We have also included some "boundary statements" that specify the level of detail students are expected to know, but standards will need to further delineate such boundaries.

The progression for practices across the grades follows a similar pattern, with grades K-2 stressing observations and explanations related to direct experiences, grades 3-5 introducing simple models that help explain observable phenomena, and a transition to more abstract and more detailed models and explanations across the grades 6-8 and 9-12. The idea behind these choices is not that young children cannot reason abstractly or imagine unseen things but that their capacity to do so in a scientific context needs to be developed with opportunities presented over time. There is ample opportunity to develop scientific thinking, argumentation, and reasoning in the context of familiar phenomena in grades K-2, and that is the experience that will best support science learning across the grades.

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