A FRAMEWORK FOR SCIENCE EDUCATION

PRELIMINARY PUBLIC DRAFT

This document is an interim draft of a report from a committee of the National Research Council (NRC) on K-12 science education in U.S. schools. It is being made public so that the authoring committee can receive comments and suggestions from interested practitioners, researchers, and the public to inform its final product.

The majority of the document we are releasing now for public comment consists of articulation of the three dimensions of the committee's framework. Each of the three dimensions of the framework–disciplinary content, cross-cutting elements, and science practices—is described in a separate section following this introduction.

Please note that full citations are not included in this version. They will be included in the final report when it is released.

A Framework for Science Education

Preliminary Public Draft

Committee on Conceptual Framework for New Science Education Standards

Board on Science Education
Division of Behavioral and Social Sciences and Education

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

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Chapter 1

Introduction: A New Conceptual Framework

The conceptual framework in this report presents the committee's vision of the scope and nature of the education in science and engineering that is needed in the 21st century. Thus, it describes the major scientific ideas and practices that all students should be familiar with by the end of high school. Engineering and technology are featured alongside the natural sciences in recognition of the importance of understanding the designed world and of the need to better integrate the teaching and learning of science, technology, engineering, and mathematics.

By a "framework" we mean a broad description of the content and sequencing for student learning and skill development in science, but not at the level of detail of grade-by-grade standards. This document is intended to act as a guide not only to Standards developers, but also to curriculum designers, assessment developers, state and district science administrators, those responsible for science teacher education, and science educators working in informal settings.

This framework is particularly timely because of a state-led national movement towards common standards across states. The growing national consensus around the need for "fewer, higher, clearer" is central to this effort. There is widespread recognition that too often standards are long lists of detailed and disconnected facts, reinforcing the criticism that the U.S. science curriculum tends to be "a mile wide and an inch deep." Not only is such an approach alienating to young people, but it can also leave students with fragmented elements of knowledge and little sense of the intellectual and creative achievements of science or its explanatory coherence.

Moreover, it neglects the need for students to develop an understanding of the practices of science and engineering which is as important as knowledge of its content.

A COHERENT VISION

This framework is an attempt to move science education toward a more coherent vision in three ways. First, it focuses on a limited number of core ideas in science and engineering both within and across the disciplines. The committee made this choice to avoid shallow coverage of a large number of topics and to allow more time for teachers and students to explore each idea in greater depth. Reduction of the sheer sum of details to be mastered gives time for students to engage in scientific investigations and argumentation and to achieve depth of understanding of the material that is included.

Second, the framework is committed to the notion of learning as an ongoing developmental progression. It is designed to help children continually build on, and revise, their knowledge and abilities, starting from initial conceptions about how the world works and curiosity about what they see around them. Its goal is to guide the development of students' knowledge toward a more scientifically based and coherent view of the natural sciences and engineering, and of the ways in which this knowledge is obtained and can be used.

Third, it emphasizes that learning about science and engineering involves the integration of both knowledge of scientific explanations (i.e., content knowledge) and the practices needed to engage in scientific inquiry and engineering design. The framework seeks to illustrate how knowledge and practice must be intertwined in designing learning experiences in K-12 science education.

The NRC's Board on Science Education has taken an active role in examining and reviewing research on science learning. Research on how children learn science and the implications for science instruction in grades K-8 was synthesized in the NRC report *Taking Science to School* (NRC, 2007). *America's Lab Report* (NRC, 2005) examined the role of laboratory experiences in high school science instruction, while *Learning Science in Informal Environments* (NRC, 2009) focused on the role of out-of-school experiences in science learning. Complementing these, the report *Systems for State Science Assessment* (NRC, 2005) looked at large-scale assessments of science learning, while the study *Engineering in K-12 Education* (NRC, 2009) looked at the skills and learning needed to introduce students to engineering during grades K-12. All of these NRC reports are essential input to the development of this framework.

The framework also builds on the prior work of the American Association for the Advancement of Science (AAAS) *Benchmarks for Scientific Literacy* and the NRC's *National Science Education Standards* (NSES). In addition, the committee examined recent efforts, including the Science Framework for the 2009 National Assessment of Educational Progress, *the Science College Board Standards for College Success* (College Board, 2009), the National Science Teachers Association's Anchors project, and a variety of state and international science standards or curriculum specifications.

Specifically, the committee was charged to develop a conceptual framework that would identify and articulate the core ideas in science around which standards should be developed by considering core ideas in the disciplines of science (life sciences, physical sciences, earth and space sciences, and engineering and technology) as well as cross-cutting ideas and practices. The committee was also charged to articulate how these disciplinary ideas and cross-cutting ideas intersect for at least 3 grade levels and to develop guidance for implementation.

PRINCIPLES OF THE FRAMEWORK

The conceptual framework described here is based on a large and growing body of research on teaching and learning science. Several guiding principles drawn from what is known about the nature of learning science underlie both the structure and content of the framework. These include young children's capacity to learn science, the need to develop students' understanding over time, the importance of considering both knowledge and practices, and the increasing importance of engineering and technology in developing understanding and using scientific knowledge and practices.

Children Are Born Investigators

Children are born investigators, studying, thinking, and building internal models of the world around them. Science is an extension of this natural curiosity to systematic investigation of the material world and the development of a body of knowledge and practices. Science education is not just a process of acquiring a body of static knowledge. It also includes developing the ability to use tools, ranging from microscopes and rulers to computers and test tubes, and the ability to build and explain models, make predictions, and conduct scientific inquiry. Just as reading, writing, and mathematics involve the performance of complex practices, so does science.

The research summarized in *Taking Science to School* (NRC, 2007) reveals that children entering kindergarten have surprisingly sophisticated ways of thinking about the natural world based on direct experiences with the physical environment, such as watching objects fall or collide, and observing animals and plants. They also learn about the world by talking with their families, pursuing hobbies, watching television, going to parks, or playing outside. As children try to understand and influence the world around them, they develop ideas about how the world works and their role in it.

In fact, young children's capacity to reason scientifically is much greater than has long been assumed. Children from all backgrounds and all socioeconomic levels show evidence of sophisticated reasoning skills. Although they may lack knowledge and experience, they can and do engage in a wide range of subtle and complex reasoning processes. These processes can form the underpinnings of scientific thinking. Thus, children begin school with a set of ideas about the physical, biological, and social worlds. By paying attention to their thinking, listening to and taking their ideas seriously, and trying to understand their thinking, educators can build on what children already know and can do. Children's ideas may be more or less cohesive, and certainly in very young children they may be underdeveloped. But these initial ideas can be used as a foundation to build remarkable understanding, even in the earliest grades. The implication of these findings is that the framework includes building explanations of natural phenomena as central throughout K-1, rather than focusing on description in the early grades and explanation only in the later grades.

Understanding Develops Over Time

The understandings of the world that children bring to school are a valuable foundation for learning science. The challenge lies in how to build successfully on this foundation. In order to develop a deep understanding of scientific explanations of the natural world, students need sustained opportunities to work with and develop the ideas that support these explanations and to understand their interconnections. Yet many science curricula consist of disconnected topics, with each given equal priority. Too little attention is paid to how students' understanding of an idea can be built on from grade to grade. Often students are continually introduced to new facts without attention to how the facts are related to each other and to the core ideas of science. As a result many, students do not develop a deep and coherent understanding of science.

Research strongly suggests that a more effective approach to science learning and teaching is to teach and develop systematically an understanding of the core ideas of science over a period of years rather than weeks or months. These core ideas offer an organizational structure for the learning of new facts, practices, and explanations, and they prepare students for deeper levels of scientific investigation and understanding in high school, college, and beyond.

The rationale for organizing content around core ideas comes from studies that show that one major difference between experts and novices in any field is the organization of their knowledge. Experts understand the core principles and theoretical frameworks of their field. Their retention of detailed information is aided by their understanding of its placement in the context of these principles and theories. Novices tend to hold disconnected and even contradictory bits of "knowledge" as isolated facts, and struggle to find a way to organize and integrate them. Learning to understand science or engineering in a more expert fashion requires development of an understanding of how facts are related to each other and to overarching core ideas. Research on learning shows building this kind of understanding is challenging, but is aided by explicit instructional support that stresses connections across different activities and learning experiences.

Research also indicates that one of the best ways for students to learn the core ideas of science is to learn successively more sophisticated ways of thinking about them over multiple years. This sense of progression and development has been conceptualized in the idea of "learning progressions". If mastery of a core concept in science is the ultimate educational destination, learning progressions provide a map of the routes that can be taken to reach that destination. A well-designed learning progression will include the essential underlying ideas and principles necessary to understand a core science concept. Learning progressions can extend all the way from preschool to twelfth grade and beyond—indeed, people can continue learning about core science concepts their whole lives. Because learning progressions extend over multiple years, they prompt educators to think about how topics are presented at each grade level so that they build on and support student learning. While there is not an extensive body of research on how children learn engineering in K-12, it is likely that a learning progressions approach would be beneficial for learning engineering as well. Hence, core ideas and learning progressions related to them are key organizing principles for the design of this framework. The tables in the next section incorporate explicitly both of these elements.

Science Is More than a Body of Knowledge

Science is not only a body of knowledge that represents current understanding of natural systems; it is also the practices whereby that body of knowledge has been established and is being continually extended, refined, and revised. Both elements – knowledge and practices — are essential. In learning science, one must come to understand both the body of knowledge and how this knowledge is established, extended, refined, and revised. The body of knowledge includes specific facts integrated and articulated into highly developed and well-tested theories supported by evidence from many investigations. These theories, in turn, can explain bodies of data and predict outcomes of investigations. They are also tools for further development of the subject.

The practices used to develop scientific theories and the form those theories take differ from one domain of science to another, but all sciences share certain common features at the core of their problem-solving and inquiry approaches. Chief among these is a commitment to evidence and data as the basis of developing claims. Therefore, argumentation and analysis that relate data and theory are essential features of science. This includes evaluation of data quality, modeling, and development of new testable questions from theory, as well as modifying theories as the need is indicated by the data. Scientists need to be able to examine, review, and evaluate their own knowledge. Holding some parts of a theory as more or less established and being aware of the ways in which that knowledge may be incomplete are critical scientific practices.

Finally, science is fundamentally a social enterprise. Scientists talk frequently with their colleagues, both formally and informally. They exchange e-mails, engage in discussions at conferences, share research techniques and analytical procedures, and present and respond to ideas via publication in journals and books. In these ways scientists are members of a scientific community whose members work together to build a body of evidence and theory.

Connecting to Students' Interests and Experiences

A rich science education has the potential to capture students' sense of wonder about the world and spark their desire to continue to learn about science throughout their lives. Research suggests that personal interest and enthusiasm are important for supporting children's participation in learning science, and may be linked to later educational and career choices. In order for students to develop a sustained interest in science and to appreciate the many ways it is relevant to their daily lives, classroom learning experiences in science need to connect with students' own interests and experiences.

As a strategy for building on prior interest, the core disciplinary ideas the committee identified are accompanied by questions that students themselves may have about the world. The prototype learning progressions are designed with an eye toward not only the knowledge students bring with them to school, but also the kinds of questions and phenomena that are likely to be of interest and accessible to them at different ages.

Promoting Equity

The issue of connecting to students' interests and experiences is particularly important for broadening participation in science. There is increasing recognition that the diverse practices and orientations that members of different cultural communities bring to formal and informal science learning contexts are assets on which to build. For example, researchers have documented that children reared in rural agricultural communities who have more intense and regular interactions with plants and animals develop more sophisticated understanding of ecology and biological species than urban and suburban children of the same age.

Others have identified connections between children's culturally based story-telling and their engagement in argumentation and science inquiry, and have documented pedagogical means of leveraging these connections to support students' science learning and promote educational equity. The research demonstrates the importance of enlisting and embracing diversity as a means of enhancing learning about science and the natural world. This will be increasingly important as U.S. society becomes progressively more diverse with respect to the language backgrounds of students and ethnic and racial group representation in society.

The goal of educational equity is one of the reasons to have rigorous standards that apply for all students. Efforts are needed to ensure that opportunities to engage in rigorous science and engineering learning are made available to all students.

STRUCTURE OF THE FRAMEWORK

Based on the guiding principles outlined above, we have created a three dimensional framework that broadly outlines the knowledge and practices all students should learn by the end of high school.

- Dimension 1 addresses specific disciplinary ideas.
- Dimension 2 includes the cross-cutting elements with applicability across science disciplines.
- Dimension 3 describes science and engineering practices.

This three-dimensional approach is not unique to this committee. Rather, it is built on and parallels many prior efforts to organize science and engineering instruction or performance expectations in ways that highlight the common features across disciplines, most recently the "Science Standards for College Success" of the College Board, and the Science Advanced Placement redesign effort. The structure also reflects discussions related to the NSTA Science Anchors effort that highlighted the need to consider both disciplinary content and the ideas and practices that cut across the science disciplines.

While the dimensions are articulated separately here, the intent is that they will be integrated in the context of standards, curriculum, instruction, and assessment. When students explore particular disciplinary ideas from Dimension 1, they will do so by engaging in practices articulated in Dimension 3 and should be helped to make connections to the cross-cutting elements in Dimension 2.

Dimension 1: Disciplinary Ideas

In organizing Dimension 1 we have grouped disciplinary ideas into four major domains – the physical sciences, the life sciences, the earth and space sciences, and engineering and technology. At the same time, we acknowledge the multiple connections among domains. Indeed, more and more frequently scientists work in interdisciplinary teams that blur traditional boundaries between the disciplines of science. We make no recommendation about course organization by the choice of how we organize the list of course content; various choices could be made that adequately and effectively engage students with this material, and multiple linkages across disciplinary boundaries are clear.

As noted, engineering and technology are incorporated as the fourth disciplinary domain. This move reflects an increasing emphasis at the national level on considering connections between science, technology, engineering and mathematics. It is also informed by a recent report from the NRC on engineering education in K-12 that highlights the interconnections between learning science and learning engineering. Engineering is a discipline that uses scientific principles to design and build useful tools and technologies, and to respond to real-world challenges and design opportunities. Just as new science enables new technologies, new technologies enable new scientific investigations, allowing scientists to probe realms and handle data quantities previously inaccessible to them. Instrumentation is critical to modern science. In addition, the line between applied science and engineering is a diffuse one. 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 see better how science and engineering apply to real world problems, and have opportunities to apply their scientific knowledge in engineering design problems when this linkage is made.

It is important to note that though we make little explicit reference in the framework to biotechnology and medical applications of science (except that bioengineering is included under the general definition of engineering used here) we do not thereby intend to downplay their importance. In fact, much of what is said about engineering could be applied in that context as well, if you think of bioengineered organisms, medical treatments, or drugs as something that you design, and that inclusion is intended here.

Dimension 2: Cross-Cutting Elements

The cross-cutting elements are those major ideas that have application across all domains of science. As such, they provide one way of linking across the domains in Dimension 1. We identified two types of cross-cutting elements. The first are cross-cutting scientific concepts. These cross-cutting concepts echo many of the unifying concepts and processes in the *National Science Education Standards*, the common themes in the AAAS *Benchmarks for Science Literacy*, and the unifying concepts in the *Standards for College Success* from the College Board.

The second type of cross-cutting element is Science, Engineering, Technology and Society. These ideas explore the historical, social, cultural, and ethical aspects of science, engineering and technology.

Dimension 3: Practices

Dimension 3 describes the practices scientists engage in as they investigate and build models and theories about the natural world. We use the term practices instead of a term like "skills" to emphasize that engaging in scientific inquiry requires coordination of both knowledge and skill simultaneously. This is to avoid the interpretation of skill as rote mastery of an activity or procedure. The practices described here are our attempt to define what was referred to as "inquiry" in previous documents. However, the components of inquiry are often specified chiefly in terms of engagement of students in experimentation or hands-on activities, and the term is interpreted in many different ways across the science education community. Part of our intent in articulating the practices in Dimension 3 is to better specify what is meant by "inquiry" in science and the range of cognitive, social, and physical practices that it requires.

Selecting Core Ideas and Practices

In selecting core ideas and practices for K-12 science instruction, the committee has developed the criteria enumerated below. Not every core idea or practice will satisfy every one of the criteria, but to be regarded as core each idea must meet more than one and preferably as many as possible of the criteria as possible. The continuing growth of scientific knowledge makes it impossible to teach all of these ideas in exhaustive detail during the K-12 years. Fortunately however, we live in an information age. Information about almost any topic is readily available; an interested and appropriately prepared student can access it readily. Given this, the role of science education is not to teach all the facts, but rather to prepare students with enough core knowledge, and to develop their ability to interpret claims and evidence so that they can begin to be informed consumers of information that is of interest to them. Strong science and engineering education about central concepts should enable them to select for appropriately reliable sources, to fit the new information into a well-structured set of understandings, and to continue their development as science learners, users of scientific knowledge and perhaps also as producers of scientific knowledge well beyond their K-12 school years.

The three dimensions of the framework -- developing understanding of disciplinary ideas, cross-cutting elements and science practices -- are here presented separately, but must be woven together in standards, curriculum, instruction and assessment, so that students gain an understanding of science as a discipline (or as a way of knowing) that supports their development of coherent and integrated knowledge about science, of the practices for applying and expanding that knowledge, and of its relationship to engineering.

A core idea for K-12 science instruction is a scientific idea or practice that:

1. Has broad importance across multiple science and/or engineering disciplines and/or is a key organizing concept of a single discipline
2. Provides a key tool for understanding or investigating more complex ideas and solving problems
3. Relates to the interests and life experiences of students or can be connected to societal or personal concerns that require scientific or technical knowledge
4. Is teachable and learnable over multiple grades at increasing levels of sophistication and depth

As a result of our effort to identify fewer core ideas of science and engineering, some scientists and educators may be disappointed to find little or nothing of their favorite science topics included in this framework. The committee is convinced that by building a strong base of core knowledge and competencies, understood at a deep enough level to be used and applied, students will leave school with a better grounding in scientific knowledge and practices and greater interest in further learning in science, than those whose instruction "covers" multiple disconnected pieces of information, to be memorized and forgotten as soon as the test is done.

IMPLICATIONS FOR STANDARDS

The committee anticipates that the most immediate use of this framework will be to guide development of new standards for K-12 science education. We envision that standards based on this framework will have the following characteristics, and will be different from prior standards in several important ways. These are summarized here and discussed in greater detail in the later chapter titled "Putting It All Together".

One difference in standards based on this framework is that they should be organized as learning progressions rather than as grade level clusters. These progressions should begin with the intuitive ideas children bring to school and be designed to help children build more sophisticated understanding over successive grades.

Another difference is that each standard should be defined as the intersection of scientific knowledge and practices. Separate standards and educational experiences for "content" or "process" should be avoided. Where possible, standards should also incorporate the cross-cutting elements, recognizing that an understanding of the cross-cutting scientific concepts or of the role of science, engineering, and technology and society will best be understood through exploration of specific examples in the disciplines.

Chapter 2

Developing Goals for K-12 Science and Engineering Education

This framework lays out a set of goals for what students should learn in science and in engineering. These goals for science and engineering education are informed, first and foremost, by a view of the essential elements of science and engineering that must be conveyed to all students. The first step in identifying these elements must be an exploration of what we perceive science to be, of the distinctions between science and engineering as practices, and of the diversity of practices engaged in by scientists and engineers.

In this chapter, we being with a brief description of key features of science and engineering and discuss the similarities and differences between them. Turning from science and engineering to science education, we review the four strands of scientific proficiency described in *Taking Science to School*. Based on the comparison of practices in science and engineering, we outline and then expand a description of the four strands to encompass both science and engineering. Finally, we describe how the strands relate to the structure of the framework.

KEY ELEMENTS OF SCIENCE

The committee's vision of science is captured by the view that science is:

- A creative and analytic human intellectual endeavor engaging hundreds of thousands of people worldwide to attain shared goals of understanding the material world and application of that understanding to solving real-world problems.
- A cumulative and evolving body of knowledge formalized into a rigorously-tested and mutually consistent set of clearly articulated theories.
- A set of practices for investigation, model and hypothesis development, theory building, argumentation, analysis, and communication of findings about the material world that support development of new understanding.
- A set of cross-cutting concepts and strategies that inform work in all disciplinary areas of the natural sciences.

The classic conception of scientific method, as it is often taught, provides only a very general and incomplete version of the work of scientists. In actual practice, the process of theory development and testing is iterative, uses both deductive and inductive logic, and incorporates many tools besides direct experimentation. Modeling (conceptual models, mechanical models, and computer simulations) and scenario building (including thought experiments) play an important role in the development of scientific knowledge. The ability to examine one's own knowledge and conceptual frameworks, to evaluate them in relation to new information or competing alternative frameworks, and to alter them by a deliberate and conscious effort are essential key scientific practices that the idealized version offered by school science textbooks fails to recognize.

Although different domains of science rely on different processes to develop scientific theories, all domains of science share certain features. First, data and evidence hold an essential position in deciding any issue. When well-established data, from experiments or observations, conflict with a hypothesis or theory, then that idea must be modified or abandoned and other explanations must be sought that can incorporate or take account of the new evidence. Theories, models, and hypotheses are rooted in empirical evidence and therefore can be tested and revised or expanded if necessary. Scientists develop and modify models, hypotheses, and theories to account for the broadest range of observations possible.

Building and testing theories is a central element of science. Through a communal process of communication, critique, and testing an idea progresses from a speculative guess to a well articulated model or a well-framed hypothesis. Eventually, after extensive testing and refinement, it may become an established and useful theory. A “useful” theory is one that is highly reliable and can provide evidence-based mechanisms for phenomena and hence can be used with confidence in designing new technologies, or in interpreting new evidence, as long as it is applied within its tested domain.

This means that scientists must not only know the existing theories relevant to their domain of investigation but also, for each theory they must know what aspects have been extensively tested, and in what domains of applicability. Thus they can tell where it can be trusted to make reliable predictions, and what aspects or domains of application are, as yet, not tested. The varying degrees of certainty of different parts of their “knowledge” are critical to shaping the arguments scientists and engineers make as they seek to interpret new evidence.

All of these elements of science involve both knowledge of scientific explanations and knowledge of and facility with scientific practices. In designing investigations, interpreting data, developing arguments, and communicating results to the broader scientific community, scientists are engaged in practices that are intimately intertwined with deep understanding of scientific explanations of the natural world.

INTEGRATING ENGINEERING

Like science, engineering is a human intellectual endeavor, with its own community of practitioners, its unique body of established knowledge and practices, its variety of specializations and its common cross-cutting ideas and approaches. These overlap with those of science but also differ from them. In particular, the goal of engineering differs from that of science. Its outcomes are products and processes rather than theories and its central discipline, rather than inquiry into natural systems, is the design of systems to serve specific purposes and solve specific problems. Similarities and differences between engineering design and scientific inquiry were discussed in the NRC report *Engineering in K-12 Education*. We summarize the discussion from this report below and then draw on it to develop a comparison of goals for science education and goals for engineering education.

Engineering Design

Design is the approach engineers use to solve engineering problems – generally, to determine the best way to make a device or process that serves a particular purpose. Engineering design is purposeful; a designer begins with an explicit goal that is clearly understood. Designs are shaped by specifications and constraints. Specifications spell out what the design is intended to accomplish. Constraints are limitations the designer must contend with, such as costs, size requirements, or the physical limitations of the materials used. The design process is systematic and iterative. Each new version of the design is tested and then modified based on what has been learned up to that point. There is never just one "correct" solution to a design challenge. Instead, there are a number of possible solutions, and choosing the most appropriate one inevitably involves personal as well as technical considerations (*Standards for Technological Literacy: Content for the Study of Technology*, ITEA, 2000). Designs also frequently lead to unintended consequences and iterative design efforts can help refine or augment a designed system for move optimal outcomes.

How Design Compares with the Scientific Practices

Engineering design is often compared with scientific inquiry and the two approaches have a number of similar features. But they differ also in significant ways. The most obvious similarity is that both design and scientific inquiry and theory-building are reasoning processes used to solve problems. For both scientists and engineers, some problems are relatively straightforward; challenging problems, however, are characterized by high levels of uncertainty that require a great deal of creativity on the part of the problem solver. In searching for solutions, engineers and scientists use similar cognitive tools, such as brainstorming, reasoning by analogy, systems thinking, mental and physical models, and mathematical and visual representations. And both require testing and evaluation of the product—the engineering design or the scientific model or theory. One point of divergence between engineering design and scientific inquiry is the role of constraints, which are common to both processes but are fundamental to engineering design. Budget constraints, for example, can limit scientific inquiry and perhaps even keep scientists from answering a particular question, but they do not affect the answer itself. For engineers, however, budget constraints can determine whether a particular design solution is workable. Another divergence is trade-offs. Trade-offs are a basic aspect of design but have essentially no part in scientific inquiry.

A further difference is the scientist's emphasis on finding general rules that describe as many phenomena as possible, whereas the engineer's focus is on finding solutions that satisfy particular circumstances. Scientific inquiry typically begins with a particular, detailed phenomenon and moves toward generalization, while engineering design applies general rules and approaches to focus on a particular solution. In addition, judgments about the suitability of a design are inevitably shaped by individual and social values; thus the optimal design for one person may not be optimal for another. This is quite different from science where values enter into choices about what to investigate and how to use the capabilities that scientific knowledge confers, but the goal is to find universal explanations of phenomena.

STRANDS OF SCIENTIFIC PROFICIENCY FOR K-12 STUDENTS

Adopting the view that science is both a body of knowledge and an evidence-based, theory and model building enterprise that continually extends, refines, and revises knowledge has implications for the kinds of learning experiences students need in order to learn science. This perspective informed the four strands of science proficiency developed in the NRC report *Taking Science to School*. These four strands describe the proficiencies that students need to develop when learning science including:

1. Knowing, using, and interpreting scientific explanations of the natural world
2. Generating and evaluating scientific evidence and explanations
3. Understanding the nature and development of scientific knowledge; and

4. Participating productively in scientific practices and discourse.

Strand 1, includes acquiring facts and the conceptual structures that incorporate those facts and using these concepts productively to understand many phenomena about the natural world. This includes using those concepts to construct and refine explanations, arguments, or models of particular phenomena.

Strand 2, generating and evaluating scientific evidence, encompasses the knowledge and skills needed to build and refine models based on evidence. This includes designing and analyzing empirical investigations and using empirical evidence to construct and defend arguments.

Strand 3, focuses on students' understanding of science as a way of knowing. Scientific knowledge is a particular kind of knowledge with its own sources, justifications, and uncertainties. Students who understand scientific knowledge recognize that predictions or explanations can be revised on the basis of seeing new evidence or developing a new model.

Strand 4, includes students' understanding of the norms for participating in science as well as students motivation and attitudes toward science. Students who see science as valuable and interesting and themselves as capable as science learners tend to be more effective learners and participants in science. They believe that steady effort in understanding science pays off – not that some people understand science and other people never will. To engage productively in science, however, students need to understand how to participate in scientific discussions, how to adopt a critical stance while respecting the contributions of others, and to be willing to ask questions and revise their own opinions.

The strands reflect the stance that learning science involves learning a system of interconnected ways of thinking in a social context to accomplish the goal of working with and understanding scientific ideas. This perspective stresses how conceptual understanding of natural systems is linked to the ability to develop explanations of phenomena and to carry out empirical investigations in order to develop or evaluate knowledge claims. These strands are not independent or separable in the practice of science, nor in the teaching and learning of science. Rather, they are mutually supportive so that students' advances in one strand tend to leverage or promote advances in other strands. Furthermore students use them together when engaging in scientific tasks.

Engineering and the Strands

The strands capture proficiencies needed for learning science; however, they do not fully capture the equivalent proficiencies for learning engineering. As discussed above, the practices of science and of engineering differ in ways that require some augmentation of the strands in order to encompass both science and engineering.

In Table 1 below we develop and expand the four strands of *Taking Science to School* to include engineering. This table demonstrates how we envision activities and practices that would support learning of science and engineering. It is structured to emphasize both the commonalities and the differences between education goals in science and engineering. The rows that stretch across the full table describe those practices that are common to both science and engineering. Where practices diverge between the two fields, the practices are shown in separate columns for science on the left and engineering on the right.

In this mapping, the areas of greatest overlap between science and engineering are in Strand 1 and Strand 4. While there are parallels between the two fields in Strands 2 and 3, there are clear differences. This is not surprising as it reflects the different goals of science and engineering. The detailed entries below the general titles for each strand are explicit practices that are part of that strand. In some cases, the specific practices go beyond the set of practices described for each strand in *Taking Science to School*.

Table 1. Target Proficiencies in Science and Engineering for K-12 Students

<table>
<tr><th>Science</th><th>Engineering</th></tr>
<tr><td>Strand 1 Know, use and interpret scientific explanations of the natural world
• Encountering and recognizing a puzzling phenomenon
• Formulating a scientific question</td><td>Strand 1 Know use and interpret scientific explanations in the designed world
• Encountering an unmet need or problem
• Defining a technological problem</td></tr>
<tr><td colspan="2">• Learning about related established scientific knowledge, and how it was developed
• Researching how others have approached similar questions/ problems, or learning more about the nature of the problem
• Reading scientific/technical books and other resources to extract information
• Using and interpreting science and engineering knowledge in written work and spoken discussion and as an element in argumentation about interpretation of evidence
• Using models to envision natural or technological systems and to make predictions</td></tr>
<tr><td>Strand 2 Generating and Evaluating Scientific Evidence
• Deciding what evidence is needed to answer a scientific question
• Formulating a testable hypothesis regarding the answer to the question
• Deciding what variables to investigate
• Planning an experiment, field study, or observation program
• Constructing or selecting instruments and measurement method
• Collecting, recording and displaying data
• Analyzing and interpreting data to establish evidence
• Constructing representations of the natural world using graphs, images, and diagrams</td><td>Strand 2: Generating and Evaluating Technological Solutions
• Determining criteria for success and constraints, or limits
• Deciding which are the most important criteria and essential constraints
• Planning an engineering design project
• Constructing or selecting resources to carry out the project
• Brainstorming, evaluating, and synthesizing initial ideas
• Comparing alternatives, making tradeoffs to optimize the solution
• Making drawings, building and testing physical and mathematical models of prototype solutions
• Determining which solutions best meet the criteria and constraints</td></tr>
<tr><td colspan="2">• Justifying explanations or optimum solutions using argument from evidence
• Identifying remaining questions or problems to solve</td></tr>
</table>

<table>
<tr>
<td>Strand 3 Understanding the nature and development of Scientific Knowledge and Capabilities
• Reflecting on evidence and argument as the source of scientific knowledge
• Recognizing that knowledge can be revised in light of new evidence</td>
<td>Strand 3 Understanding the nature and development of Technological Knowledge and Capabilities
• Reflecting on creativity and analysis in the development of technologies
• Recognizing that technologies or designs can always be improved</td>
</tr>
<tr>
<td colspan="2">• Understanding the interplay of science, technology and society
• Reflecting on the status of their own knowledge and ways of thinking
• Using systems thinking and explicit models to refine their own mental models</td>
</tr>
<tr>
<td colspan="2">Strand 4. Participating Productively in practices and discourse of Science or Engineering
• Motivated to learn about science and engineering
• Forming a self-identity as a science and engineering learner and problem solver
• Skillfully interacting with peers and working in teams
• Representing information and ideas clearly and convincingly
• Arguing logically from evidence
• Respectfully listening and responding to the ideas of others
• Questioning one's own ideas and modifying them in the light of evidence
• Engaging in designing solutions to practical problems using science knowledge relevant to the context</td>
</tr>
</table>

THE STRANDS AND THIS FRAMEWORK

While the strands are useful for thinking about proficiencies that students need to develop, as framed they do not describe in any detail what it is that students need to learn and practice. Thus, they cannot guide standards, curricula or assessment. Further specification of the knowledge and practices students must learn is needed. The three dimensions that are developed in this framework – disciplinary core ideas, cross-cutting elements, and practices -- make that specification. These three dimensions frame a space of ideas and practices of science and engineering within which the four strands can be woven in many ways. There is no simple translation between the strands and the dimensions; however, they represent a common view of the richness and variety of work needed to develop student understanding of, and competencies in science and engineering.

Chapter 3

Dimension 1: Core Disciplinary Ideas

The committee's framework organizes disciplinary ideas in four major areas: life sciences, earth and space sciences, physical sciences, and engineering and technology. For each area, we present the major core ideas and their components. Each core idea and component of a core idea is accompanied by a question and given a shorthand label for ease of reference. The questions are designed to show what aspects of the world each core idea and its components help to explain. They also make clear that posing and seeking to answer questions about the world is fundamental to doing science. In addition, the questions are designed to relate to questions students may have about the world or that they need to be able to answer in order to understand the country's current and emerging major social, technological, and environmental issues.

In a separate chapter titled "Prototype Learning Progressions," we present a detailed sequence for each core idea in each discipline to show how that idea can be developed across four grade level bands, K-2, 3-5, 6-8, and 9-12.

CORE IDEAS IN THE LIFE SCIENCES

LS 1: Organisms have structures and functions that facilitate their life processes, growth, and reproduction. (From Molecules to Organisms – Structures and Processes)

How do living things do what they need to so they can live, grow, and reproduce?

The characteristic feature of life is that organisms grow, breathe, reproduce and die. Organisms have characteristic structures (anatomy and morphology) and functions (physiology) to support life processes. Organisms and their parts are made of cells, which are the structural and functional units of life, and which themselves have molecular substructures that support their functioning. The characteristic structures (anatomy) and functions (physiology) of organisms change in predictable ways as they develop, from birth to old age.

Organisms deploy a variety of chemical reactions to live and grow. These functions require the input of energy. In most cases, the energy needed is ultimately derived from the sun. Plants and other energy-fixing organisms, such as bacteria, use sunlight and chemical compounds from the air, water and soil to facilitate a chemical process (photosynthesis) that stores energy, forms plant matter and maintains plants' activities; these organisms sustain the rest of the food web. The complex structural organization of organisms accommodates the need for obtaining, transforming, transporting, releasing, and eliminating the matter and energy used to sustain them.

LS1.A. *How do the structures of organisms help them to perform life's functions?* (Structure and Function)

LS1.B. *How do the structure and functioning of organisms change as they grow and develop?* (Growth and Development of Organisms)

LS1.C. *How do organisms get and use the matter and energy they need to live and grow?* (Organization for Matter and Energy Flow in Organisms)

LS 2: Organisms have mechanisms and processes for passing traits and variations of traits from one generation to the next. (Heredity -- Inheritance and Variation of Traits)

How are characteristics of one generation of organisms passed to the next and what are the consequences regarding inheritance and variation across generations?

Inheritance is the key factor in similarity among individuals within a population or species. Organisms pass information from one generation to the next via units called "genes." When organisms reproduce they transfer genetic information to their offspring. Genes control the characteristics or traits of the organism as it develops, although environmental factors may modify development and appearance of an individual. Thus genes and genes by environment interactions determine how organisms look and perform. Variations of inherited traits between parent and offspring arise from genetic differences that result from genetic recombinations occuring during sexual reproduction or, more rarely, from mutations.

LS2.A. *How are the characteristics of one generation of organisms related to the next generation?* (Inheritance of Traits)

LS2.B. *Why do individuals of the same species vary in how they look and function?* (Variation of Traits)

LS 3: Organisms and populations of organisms obtain necessary resources from their environment which includes other organisms and physical factors. (Ecosystems: Interactions, Energy, and Dynamics)

How and why do organisms interact with other organisms and their environment? What happens to ecosystems as a result of these interactions?

Organisms must obtain the necessary resources for life from their environment, which consists of other organisms (biotic factors) and physical (abiotic) factors. Organisms (individuals) constituting populations and species live in ecosystems, in which they interact with one another in complex feeding relationships, competing with and/or supporting one another in obtaining needed material and energy resources. Materials cycle within ecosystems through interaction with different organisms which are organized in different levels of food chains, from producers to decomposers. Ecosystems are continuously changing. Changes in environmental factors can result in changes in populations and species, in the maintenance or extinction of species in the ecosystem, or in migration of species into or out of the region. Ecosystems with a wide variety of species tend to be more resilient to change than those with few species.

LS3.A. *How do organisms depend on the feeding relationships of one another and of the physical (abiotic) environment?* (Interdependent Relationships in Ecosystems)

LS3.B. *How do organisms in an ecosystem get the materials and energy they need?* (Flow of Matter and Energy Transfer in Ecosystems)

LS3.C. *What happens to organisms and ecosystems when there are changes in the environment?* (Ecosystems Dynamics, Stability, and Resilience)

LS 4 Biological evolution explains the unity and diversity of species. (Biological Evolution: Unity and Diversity)

How can we explain the many different kinds of plants, animals, and microorganisms? Why are there are so many similarities among organisms? More generally, how can the diversity within this unity be explained? What is the relationship between biodiversity and humans?

Biological evolution explains both the unity and diversity of species. Biological evolution results from the interactions of (1) the potential for a species to increase its members, (2) the genetic variation of individuals within a species due to mutations and recombinations of genes, (3) a finite supply of the resources required for individuals to survive and reproduce, and (4) the ensuing selection by the environment of those organisms better able to survive and reproduce. Organic evolution, and the net result of speciation minus extinction, has led to the planet's biodiversity and ecosystem functioning. Sustaining biodiversity is essential for the maintenance and enhancement of the human population's quality of life.

The fossil record provides evidence of different life forms at different periods of geological history. This evidence supports the idea that newer life forms descended from older life forms, a phenomenon that Darwin aptly called "descent with modification". DNA provides further evidence for lines of descent from ancestral species to later-appearing species.

Genetic variation of individuals within a species gives some individuals an advantage to survive and reproduce in the conditions of their environment. This leads to the predominance of certain inherited traits within a varied population. When an environment changes, there is a subsequent change in the supply of resources or in the challenges imposed by abiotic and biotic factors of the environment. This results in selective pressures that influence the survival and reproduction of organisms and which lead to adaptations, that is to changes in the traits of survivors within populations, and to extinction of species unable to adapt to such changes. Mutations most often produce non-viable individuals, but, infrequently, can introduce new traits within a population that offer survival advantages. Many such changes, along with reproductive isolation and the selective pressures from the environment can lead to the development of adaptations and, eventually, to distinct new species.

Biodiversity – the diversity of genes, species, and ecosystems – provide humans with renewable resources such as food, fuels, fertile soils, clean water and air, medicines, as well as surroundings (from species to landscapes) of inspirational value. The resources of biological communities can be used within sustainable limits, but in many cases the human impact is exceeding sustainable limits.

LS4A. *How have organisms changed over time?* (Evidence of Common Ancestry and Diversity)

LS4.B *How does variation in organisms affect survival and reproduction?* (Genetic Variation in a Species)

LS4.C. *How does the environment influence populations of organisms?* (Natural Selection and Adaptation)

LS4.D. *What is biodiversity and how do humans affect it and how does it affect humans?* (Biodiversity and Humans)

CORE IDEAS IN THE EARTH AND SPACE SCIENCES

ESS 1: Humans are a small part of a vast Universe; planet Earth is part of the Solar System, which is part of the Milky Way galaxy, which is one of hundreds of billions of galaxies in the Universe. (The Solar System, Galaxy, and Universe)

What is our place in the Universe and how do we know?

Earth is one planet of a single star in a galaxy of hundreds of billions of stars; telescopes allow us to see hundreds of billions of galaxies extending far in all directions in complex patterns of matter and space. Space in this huge system that we call the observable Universe is expanding, and has been since the Big Bang, a very rapid stage of expansion 13.7 billion years ago. All this is known from matching theory and models with multiple threads of observational evidence.

Within this Universe, all the structures we see – the stars, planets, and galaxies – move in patterns controlled by gravity, and were formed by the action of gravity on condensing clouds of gas and dust. Stars radiate energy released by nuclear fusion in their cores; some end their lives as supernovae, thereby producing and distributing material containing all the elements into space. This material is then recycled by gravity into later-developing stars and planetary systems. Chemical and isotopic abundances provide evidence that the Solar System and all its planets formed in this way more than four billion years ago. Gravity also controls the motions of the Earth and Moon, and of all the solar system planets, relative to the sun. These motions explain many observed patterns of change of objects in the sky as seen from Earth.

ESS 1.A. *What is the Universe?* (The Universe)

ESS 1.B. *What forces and processes govern motion, matter and structure in the universe?* (Gravity, Energy and Matter in the Universe)

ESS 1.C. *What is Earth's relationship to other objects in our solar system?* (Earth and the Solar System)

ESS 2: Earth is a complex and dynamic 4.6-billion-year-old system of rock, water, air, and life. (Earth's Planet-sized Structures, Processes and History)

What processes drive change in Earth's large-scale structure?

Earth is a dynamic planet, changing over time. Tectonic plates move across the Earth's surface, carrying the continents, creating and destroying ocean basins, setting off earthquakes and volcanoes, and pushing up mountain ranges. These plates are the top parts of giant convection cells that bring hot materials from the deep mantle up to the surface to cool off, then fall back in. Viewed as an interacting system, Earth includes the deep interior of the planet, the rock and metal of the surface tectonic plates (the geosphere), the water and air of the hydrosphere and atmosphere, and the living organisms of the biosphere. Earth's rocks and other materials provide a record of its 4.6 billion-year-old history, which can be deciphered from fossil-bearing layers and radioactive and other dating methods.

ESS 2.A. *What changes the positions of the continents over time?* (Continental Drift, Plate Tectonics, and Earth's Internal Heat)

ESS 2.B. *What is planet Earth made of?* (Earth's Materials)

ESS 2.C. *How old is Earth and how do we know the timing of events in its history*? (Earth's History)

ESS 3: Earth's surface continually changes from the cycling of water and rock driven by sunlight and gravity. (**Earth's Surface Processes and Changes)**

Why do we call Earth the water planet?

The sun's energy and the Earth's gravity and rotation drive dynamic processes in the ocean and atmosphere, creating flows of water and energy that interact with surface landforms and life-forms to determine weather and climate and cause changes in the surface systems. Water's unique properties play critical roles in all Earth surface systems. Earth's surface materials are continually moved around and changed from one form to another, by the action of water, ice and plate motion. Weather and climate are regulated by complex interactions among the components of the Earth's system and change over varying time scales. Water-dependent life developed and evolves on a dynamic Earth and continuously modifies the planet, and is modified by changes in the planet.

ESS 3.A. *How do the properties and movements of water affect Earth's systems*? (The Role of Water in Earth's Surface Processes)

ESS3.B. *How does Earth's solid matter cycle on Earth's surface over time*? (Formation and alteration of rocks and landforms)

ESS 3.C. *What regulates weather and climate*? (Weather and Climate)

ESS 3.D. *How does life interact with Earth's other systems*? (Biogeology)

ESS 4: Human activities are constrained by and, in turn, affect all other processes at Earth's surface. (Human Interactions with Earth)

How do humans affect the Earth, and how do Earth's changes affect humans?

Humans depend on the Earth's conditions and its resources for survival. Natural events and human actions interact, and can change the balance of human and earth systems. Natural Earth processes can cause both sudden and gradual changes to Earth's systems that can adversely affect humans. Understanding local risks of these hazards is important for the preparation and response to them.

Humans depend upon Earth for many different resources, including air, water, soil, rocks, minerals, metals, and sources of energy. The activities and resource use that have built human civilizations and supported human population growth have both positive and negative consequences related to the sustainability of these civilizations and populations. Human activities have become one of the most significant agents of geologic and ecologic change at Earth's surface today. Climate change, which is driven by both natural processes and human activities, has large consequences for all of Earth's surface systems, including humans. Human choices can affect future climate change.

ESS 4.A. *How do natural hazards affect humans? (*Natural Hazards)

ESS 4.B *How do humans depend upon Earth's materials? (*Natural Resources)

ESS 4.B. *How do humans change the Earth? (*Human Impacts on the Earth)

ESS 4.C. *How will global climate change affect humans?* (Global Climate Change)

CORE IDEAS IN THE PHYSICAL SCIENCES

PS 1: Macroscopic states and characteristic properties of matter depend on the type, arrangement and motion of particles at the molecular and atomic scales. (Structure and Properties of Matter)

What are substances made from and how does their structure affect their properties?

The properties of substances experienced at the macroscale depend on the type, arrangement and motion of extremely small particles at the molecular and atomic scales. All substances are made up of atoms that are in constant motion. Atoms themselves have substructure which determines how they combine, arrange and interact to form all substances. Substances have characteristic measurable properties that depend on their atomic level substructure. Only a few of these properties are meaningful at the atomic scale; most are descriptions of bulk matter. Understanding these properties allows scientists to decipher the composition of objects and engineers to design systems using appropriate materials.

PS 1.A. *What makes up everything around us?* (Atomic Structure of Matter)

PS 1.B. *How can you distinguish one substance from another? (*Properties of Matter)

PS 2: Forces due to fundamental interactions underlie all matter, structures and transformations; balance or imbalance of forces determines stability and change within all systems. (Interactions, Stability, and Change)

What happens when matter interacts or changes and how do we characterize, explain, and predict what will happen immediately and over time?

Interactions affect the structure, properties and behavior of matter. Interactions result in forces that may induce change or maintain stability in systems. All known physical phenomena can be explained by only a few types of interactions: gravitational, electromagnetic, and, at the nuclear scale, strong and weak interactions. These interactions are the source of forces between particles and particle decays. Unbalanced forces cause change in motion; balanced forces lead to stability, that is, to no change. Interactions may induce transformations of matter. When a transformation occurs, some things in a system change while others stay the same. Different factors affect the rate of different transformations. (Transformations here include both physical and chemical changes.)

PS 2.A. *What are the interactions that help explain phenomena at all scales?* (Fundamental Interactions)

PS 2.B. *How can we predict the continued motion, changes in motion, or stability of an object?* (Motion and Stability)

PS 2.C. *What happens when matter transforms and how do we characterize, explain and make predictions about the transformations?* (Transformations of matter)

PS 3: Transfers of energy within and between systems never change the total amount of energy, but energy tends to become more dispersed; energy availability regulates what can occur in any process. (Energy and its Transformations)

What is energy? Why is it important?

All processes involve transfers of energy within and between systems. The concept of energy is useful because the total energy never changes and its availability limits what can occur in every interaction. At the macroscale, energy can be accounted for in many different forms. At the atomic scale, all forms of energy can be described in terms of kinetic energy, radiation, and energy that can be released or absorbed due to changes in the state of a system of interacting particles. All forms of energy can be quantified. Energy can be transferred from one system to another and transformed from one form to another, but it cannot be created or destroyed.

In everyday language we speak of producing, using or wasting energy. This is because energy that is in concentrated form is useful for running machines, generating electricity for heat and light etc., while dissipated energy in the environment is not readily recaptured. Most processes tend to dissipate energy. Food, fuel and electric power are concentrated energy resources that can be moved from place to place to provide energy where needed. Food and fuel contain carbohydrates. These substances react with oxygen in burning or digestive processes to release thermal energy and carbon dioxide and other by-products. This process is a key energy provider for most animal life and for many forms of electrical generation, transportation and industrial machines.

Forces between two objects indicate that there is energy stored between them due to some interaction (e.g. gravitational, electromagnetic). Forces between two interacting objects are always in a direction such that motion in that direction would reduce the energy in the force field between them, but prior motion and other forces affect the actual direction of motion.

PS3.A *What is energy?* (Descriptions of Energy)

PS3.B *If energy is conserved, how can we use it? How do food and fuel give us energy?* (Energy for life and practical use: The special role of food and fuel)

PS3.C *Forces and energy transfer are both involved in changes of motion, how are they related?* (Relationship Between Energy and Forces)

PS4: Our understanding of wave properties, together with appropriate instrumentation, allows us to use waves, particularly electromagnetic and sound waves, to investigate nature on all scales, far beyond our direct sense perception. (Waves as carriers of energy and information)

What is so special about waves? In what sense are light and sound waves?

Waves carry energy and information, without net motion of matter, from a source to a detector. Waves combine with other waves of the same type to produce complex patterns containing information that can be decoded by detecting and analyzing them.

Light and sound are major ways that we gain information and interpret the world around us. Our understanding of their wave properties, and of wave behavior in general, inform our models of how they interact with matter and how we can detect and interpret information carried in these signals. Light and other electromagnetic waves are extremely useful as probes of phenomena on scales from the very large to the very small, far beyond the range of our direct sense perception. Instrumentation to produce, detect and interpret waves is a key tool in probing otherwise invisible systems and in communication and information technologies.

PS4.A *What are the characteristic properties and behaviors of waves?* (Wave properties)

PS4.B *What is an electromagnetic wave or electromagnetic radiation?* (Electromagnetic radiation)

PS4.C. *How do we use instruments that transmit and detect light and sound to extend our senses?* (Detection and interpretation, Instrumentation)

CORE IDEAS IN ENGINEERING AND TECHNOLOGY

ET 1: The study of the designed world is the study of designed systems, processes, materials and products and of the technologies and the scientific principles by which they function. (The Designed World)

What are the products, processes, and systems that constitute the designed world and how have they come to exist?

The designed world is comprised of the technological systems, processes, and products that humans have built and with which they interact. The designed world and the natural world co-exist and in some ways are interdependent. The fundamental building block of the designed world is technology -- the products, systems and processes created by engineers, technologists, and scientists with input from many others such as politicians and ordinary citizens to meet people's needs and wants. Technology both affects and is affected by the decisions people make as workers and consumers, and in day-to-day life. It also reflects the cultural values and norms of a society.

The designed world is constantly changing as new technologies, tools and materials are developed. A tool is a physical or cyber object that improves people's abilities to design, build and utilize products, processes and systems; to cut, shape, or put together materials, to move things from one place to another, or to grow and process food.

ET1.A. *Why were the various products, processes and systems that enable everyday life developed?* (Products, Processes and Systems)

ET1.B. *What is technology and how does technological development shape our world?* (Nature of Technology)

ET1.C. *How do people use tools and materials to modify or create new technologies?* (Using Tools and Materials)

ET 2: Engineering design is a creative and iterative process for identifying and solving problems in the face of various constraints. (Engineering Design)

How are the systems, processes and products of the designed world created?

Engineering design is a powerful but by no means prescriptive approach to defining and solving technological problems in the face of time, resource, economic, environmental, social, and ethical constraints. Engineering problems are created by a human need or want and can be defined in terms of criteria and constraints or limits. Design is a non-linear, iterative process that typically includes problem identification, research, brainstorming, and optimization and the design of possible solutions. As a first step, it is important to find out how others have solved similar problems and to learn more about the nature of the problem itself.

Finding a solution starts with a creative process that leads to synthesis, focus, and rigorous testing of potential solutions. Building and testing prototypes or physical and mathematical models is an important part of engineering design, as is analysis of data resulting from this testing. Finding the best solution often requires making decisions regarding tradeoffs among competing criteria. This is a process called optimization.

ET2.A. *How are technological problems defined and researched?* (Defining and Researching Technological Problems)

ET2.B. *How are creative solutions developed and evaluated?* (Generating and Evaluating Solutions)

ET2.C. *How can the best possible solution be developed to solve a technological problem?* (Optimizing and Making Tradeoffs)

ET 3: People are surrounded and supported by technological systems. Effectively using and improving these systems is essential for long-term survival and prosperity. (Technological Systems)

How are technological systems designed and produced? How do they interact with natural systems? How can systems thinking help people solve problems and design better systems?

People are surrounded and supported by technological systems. Effectively using and improving these systems is essential for long-term survival and prosperity. In very general terms a system is a collection of interacting pieces (see Chapter 4, Dimension 2: Cross-Cutting

Concepts for a longer discussion of systems). Many technologies are both part of a larger system and themselves comprised of subsystems. Like natural systems, technological systems have identifiable structures, functions and behaviors. They receive inputs and produce outputs, have boundaries, and their behavior is moderated through processes of feedback and control. In order to design technology, engineers must have a good grasp of how technological systems work and what factors influence the performance of the system.

In order to design technological systems that allow for safe and economical use with minimal impact on the environment, it is helpful to analyze a system's entire life cycle, which begins with raw materials, continues through processing, shipment, sales, use and maintenance, and eventually ends with disposal or recycling. System maintenance is the process by which systems are inspected and maintained. Careful maintenance extends the lifetime of the system and reduces its operational cost.

ET3.A. *What are technological systems and how can they best be modeled and improved?* (Identifying and modeling technological systems)

ET3.B. *How can life- cycle analysis be utilized to improve technological designs?* (Life cycles and maintenance of technological systems)

ET3.C. *What are control systems and feedback systems, why are they effective, and how can they be improved?* (Control and Feedback)

ET4: In today's modern world everyone makes technological decisions that affect or are affected by technology on a daily basis. Consequently, it is essential for all citizens to understand the risks and responsibilities that accompany such decisions. (Technology and Society)

What are the responsibilities of all citizens with respect to technological decision-making?

Technology influences society just as society influences technology. The development of technology is driven by the needs and desires of people, and technology can have both positive and negative impacts on people and the environment. Throughout history and across cultures and continents, technology has played a major role in shaping societal change. Technologies such as those for food production, sanitary water supply, warfare, transportation, and long-distance communication have dramatically influenced where, how, and how long people live. Making thoughtful decisions about the development and use of technology, including considering trade-offs between benefits and risks, is an important characteristic of being technologically literate.

ET4.A. *What are the societal risks and benefits of technology?* (Interactions of technology and society)

ET4.B. *How have the development and uses of technologies brought about changes in the natural environment and human culture?* (Interactions of technology and environment)

ET4.C. *How can citizens analyze issues about technology and society?* (Analyzing issues involving technology and society)

Chapter 4

Dimension 2: Cross-Cutting Elements

In this chapter we describe two types of cross-cutting elements of science and engineering. The first are scientific concepts that bridge across disciplinary boundaries and have explanatory value throughout much of science and engineering. These concepts need to be made explicit for students because they provide an organizational framework for accumulating and inter-relating knowledge from all the various disciplines knowledge into a coherent and scientifically-based view of the world.

The second set of cross-cutting elements explores the links between science, engineering and society, and, more particularly, the links to student's lives. These include the history and cultural roles of science and technology; the effects of science and technology on society; the effects of societal norms and values on the practices of science and engineering; the professional responsibilities of scientists, engineers, and medical professionals; the roles of science and technical knowledge in personal decisions; and careers and professions in and using science and engineering. Each of these topics is of relevance to students and must be part of what is discussed in the science classroom across the years of their education.

Though these concepts are fundamental to an understanding of science, students are often expected to build such knowledge without any explicit instructional support. Hence, the purpose of highlighting them as Dimension 2 of the science framework is to elevate their significance in the development of science standards, curriculum, and assessment. The goal is not to isolate these cross-cutting elements as separate standards, or as separate units in a curriculum. Rather, in keeping with the vision of the framework that standards should be written as the intersection of Dimensions 1, 2 and 3, the cross-cutting elements are common touchstones across the disciplines and across grade-levels. Explicit reference to and development of these elements of science in multiple disciplinary contexts can help students develop an integrated, cumulative and usable understanding of science.

While we do not present explicit learning progressions for these elements, each of them can appear with increasing sophistication as students mature. Like all learning in science, students' facility and sophistication in addressing these concepts and topics at a particular grade level depends on their prior experience and instruction.

CROSS-CUTTING SCIENTIFIC CONCEPTS

"Some important themes pervade science, mathematics, and technology and appear over and over again, whether we are looking at an ancient civilization, the human body, or a comet. They are ideas that transcend disciplinary boundaries and prove fruitful in explanation, in theory, in observation, and in design." (*Science for All Americans*, p. 165).

The committee identified the following seven cross-cutting scientific concepts:

- *Patterns, similarity, and diversity*

  Observed patterns in nature guide organization and classification, and prompt questions about relationships and causes underlying them.

- *Cause and effect: mechanism and prediction*

  Events have causes, sometimes simple, sometime multifaceted. Deciphering causal relationships, and the mechanisms by which they are mediated, is a major activity of science.

- *Scale, proportion, and quantity*

  In considering phenomena, it is critical to recognize what is relevant at different size, time and energy scales, and to recognize proportional relationships between different quantities as scales change.

- *Systems and system models*

  Delimiting and defining the system under study and making a model of it are tools for developing understanding used throughout science and engineering.

- *Energy and matter: flows, cycles and conservation*

  Tracking energy and matter flows, into, out of, and within systems helps one understand their system's behavior.

- *Form and function*

  The way an object is shaped or structured determines many of its properties and functions.

- *Stability and change*

  For both designed and natural systems, conditions of stability and what controls rates of change are critical elements to consider and understand.

The set begins with two concepts that are very general roots of science: patterns can be explained, and science elucidates cause-and-effect relationships by seeking the mechanism that underlies those relationships.

The next concept, scale, proportion and quantity, covers the sizes of things and the proportional and more complex mathematical relationships between disparate quantities.

The next four concepts—systems and system models, energy and matter flows, form and function, and stability and change—are interrelated in that the first is illuminated by the next three. They also each stand alone as important concepts that occur across all areas of science and are important considerations for engineered systems.

This set incorporates concepts that appear in other standards documents and have been referred to as unifying concepts (*NSES* and the *Science College Board Standards for College Success*) or common themes (in AAAS *Benchmarks for Science Literacy*). The listed set of cross-cutting concepts that have power across the science curriculum is very similar across these documents, varying chiefly in how ideas are grouped or separated, and in the labels chosen to summarize them.

Patterns, Similarity, and Diversity

Observed patterns in nature guide organization and classification, and prompt questions about relationships and causes underlying them.

Patterns exist everywhere in regularly occurring shapes or structures, repeating events, or repeated relationships: patterns such as the symmetry of flowers or snowflakes, the regular passing of the seasons and the repeated base pairs of DNA. Noticing patterns in the material world is often a first step to asking scientific questions

One major use of pattern recognition is in classification. Classification depends on pattern recognition and careful observation of similarities and differences. Objects can be classified into groups on the basis of similarities of visible or microscopic features or on the basis of similarities of function. Classification is useful in order to codify relationships, and organize a multitude of objects or processes into a limited number of groups. Patterns of similarity and difference and thus classifications may change depending on the scale at which a phenomenon is being observed. For example, isotopes of a given element are different because they contain different numbers of neutrons, but from the perspective of chemistry, they can be classified as the same because they have identical patterns of chemical interactions.

Naming and classifying facilitate precise observation and supports both recognition of patterns and identification of changes in them. For example, a trained observer can instantly recognize many differences between plants that look similar to the untrained eye. Once a pattern or relationship is recognized, it is often useful to develop a mathematical representation of it and with that as a tool to seek an underlying explanation for what causes the pattern to occur. For example, the pattern of floating and sinking of compact solid objects can be mathematically represented by a graph comparing outcomes based on the density of the solid and that of the fluid.

It is important for students to develop ways to recognize and record patterns in the events and phenomena they observe. Young children begin recognizing patterns in their own lives well before coming to school, because patterns are ubiquitous. The sun and moon follow consistent daily patterns. The seasons follow patterns that elementary students can observe and describe. Students should also begin analyzing patterns in rates of change and cycles. More advanced students can begin relating patterns to the nature of microscopic and atomic-level structure, energy transfer and transformation, and the underlying forces and interactions.

Cause and Effect: Mechanism and Prediction

Events have causes, sometimes simple, sometimes multifaceted. Deciphering causal relationships, and the mechanisms by which they are mediated, is a major activity of science.

Many of the most productive and compelling questions in science are questions about why or how something happens. Such questions are aimed at uncovering the causes of phenomena. Any hypothesis that A causes B requires a model for the chain of interactions that connect A and B. A major activity of science is to uncover and understand these causal connections, often with the hope that understanding will make it possible to make predictions.

Repeating patterns in nature or events that occur together with regularity are clues that scientists can use to start exploring causal relationships. There are cause-and-effect relationships to be explored across all the disciplines of science, for example, in population changes, in disease spread, in physical or chemical systems, or in understanding a hole developing in the ozone layer over the poles.

While identifying cause and effect may seem straightforward in simple cases, such as a bat hitting a ball, in complex systems causation can be difficult to tease out. Sometimes causation can be deterministic, that is, one event will reliably lead to the same outcome, such as a ball falling to the ground when it is thrown in the air. In many cases, causation can only be described in a probabilistic fashion, that is, there is some likelihood that one event will lead to another, but a specific outcome cannot be guaranteed. For example, one can predict the probability that an atom will undergo radioactive decay in a certain time period, but not the time at which it will decay. Causation can also be conditional, depending on multiple factors, so that A can cause B only if some other factors are in place or within a certain range. For example, seeds germinate and produce plants, but only if sufficient moisture is available in the soil.

One fundamental assumption of all science is that there is a self-consistent, limited and universal set of fundamental physical interactions that underlie all known forces, and hence are a root part of any causal chain, whether in natural or designed systems. "Universality" means that the physical laws of interactions are the same everywhere and at all times. All known processes depend on gravity, electromagnetism and/or the weak and strong nuclear interactions. At a larger scale, in biological systems the universality of life appears in a common genetic code. However, throughout biology, the inner workings of a cell, or even of a brain, can be understood in terms of the same understandings from physics and chemistry that apply in nonliving systems.

In engineering, the goal is to design a system to cause a desired effect, so cause and effect relationships are as much a part of engineering thinking as of science. Indeed the process of design is a good place to help students to begin to think in terms of cause and effect, because they are effectively forced to do so in asking what design will achieve their goal.

One goal of instruction about cause and effect is to encourage students to see events in the world as having understandable causes, even when these causes are beyond human control. The ability to distinguish between scientific claims about causation and nonscientific claims is also an important goal.

Students with a basic understanding of science can begin to analyze patterns in the rate of change and cycles, and to look for mathematical patterns of relationships between different quantities in data. Such patterns are clues to cause-and-effect relationships that can explain the observed patterns.

More advanced students can be asked to connect their ideas of cause and effect with standard scientific theories that relate to the mechanisms of causation in the systems under study. Strategies for this type of instruction include requiring students to provide evidence for attributing a cause to an observed relationship or phenomenon. For example, students exploring why the population of a given species is shrinking will look for factors in the ecosystem that lead to lack of food, over-predation or changes in other survival factors in the habitat that they can show affect that species in particular.

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Scale, Proportion, and Quantity

In considering phenomena, it is critical to recognize what is relevant at different size, time and energy scales, and the proportional relationships between different quantities as scales change.

Systems and processes in nature vary in size, time span and in the amount of energy flowing through them. These differences in magnitude are referred to as scale. Understanding relative magnitude is only a starting point to the idea of scale. As noted in *Benchmarks for Science Literacy*, "the large idea is that the way in which things work may change with scale. Different aspects of nature change at different rates with changes in scale, and so the relationships among them change, too." For example, when working on larger size scales, such as mountain ranges, one typically needs to consider change that occurs over large time scales. On the other hand small scale systems, such as a cell, can be viewed over much shorter times. However, processes that occur locally and on short time scales can have long term and large scale impacts as well.

In developing a concept of the very small and the very large, both in space and in time, it is important to have a sense not only of numerical ratios of scale sizes, but of what ideas and concepts are meaningful at what scale. For example the concept of solid matter is meaningless at the sub-atomic scale, and the concept that light takes time to travel a given distance becomes more important and meaningful as one looks at large distances across the Universe.

Understanding scale requires some understanding of measurement and relative quantity. At a basic level, in order to identify something as "bigger" or "smaller" and how much bigger or smaller, a student must understand the units used to measure it. To understand the relative magnitude of some properties or processes, it may be necessary to understand the relationships between different types of quantities, for example, speed as the ratio of distance travelled to time taken, or density as a ratio of mass to volume. Recognition of such relationships between different quantities is a key step in forming mathematical models that interpret scientific data. The ideas of ratio and proportionality as used in science extend and challenge students' mathematical understanding of these concepts. Explicit instruction is needed for students to assign meaning to the types of ratios and proportional relationships that they meet in science.

Engineering design makes use of precise scale diagrams and the design of structures must incorporate appropriate understanding of scale relationships, so engineering design activity supports students in developing facility with this important concept.

Scale is a concept that builds from the early grades to provide understanding natural phenomena. Young children begin understanding scale with objects and time related to their world, and with explicit scale models and maps. They can begin by discussing the biggest and smallest, or fastest and slowest without reference to particular scales of measurement. As students become familiar with linear measurement, they can expand their understanding of scale to include mass, time, and temperature, and other scales. As students become more sophisticated, it is useful to help them develop a sense of the scale of various objects and systems, and to be able to move back and forth between models at various scales depending on the question being considered. Advanced students should have a sense of the powers of ten scales and what phenomena correspond to what scale, from the size of a nucleus of an atom to the size of the galaxy and beyond.

Systems and System Models

Delimiting and defining the system under study and making a model of it are tools for developing understanding used throughout science and engineering.

"The natural and designed world is complex; it is too large and complicated to investigate and comprehend all at once. Scientists and students learn to define small portions for the convenience of investigation. The units of investigations can be referred to as "systems". A system is an organized group of related objects or components that form a whole. Systems can consist, for example, of organisms, machines, fundamental particles, galaxies, ideas, and numbers. Systems have boundaries, components, resources flow, and feedback." (*NSES*).

The parts of a system are interdependent and each component depends on or supports the functioning of the other parts of the system. However, the properties and behavior of the whole system can be very different from that of any of its parts.

Although any real system (smaller than the entire universe) interacts with and is dependent upon other external systems, it is often useful to conceptually isolate a limited system for study. To do this scientists or engineers imagine an artificial boundary between the system in question and everything else. They then examine and model the system in detail while treating the effects of things outside the boundary only in terms of the forces, matter and energy that flow across the boundary (e.g., the gravitational effect of the earth in the case of a book lying on a table). Organisms or engineered systems often have a more obvious definition of a boundary, but again consideration of flows into and out of the system (inputs, outputs, waste products) is a crucial element of systems design.

Things viewed as subsystems of a system at one scale can themselves be viewed as systems at a smaller scale. For example, the digestive system may be studied as a separate system, but also as a subsystem of the entire human body; a molecule can be studied as a system of atoms, but also considered as a sub-system when studying properties of gases.

In order to understand the functioning of a system, scientists and engineers develop models of the system, that describe not only the parts of the system but also the interactions (forces, energy and matter exchanges) between them. Models are useful tools for understanding how components of the system are related to each other, predicting their behaviors, and diagnosing their failures. A model is any representation of a system that has explanatory or predictive power. Models may include analogies, physical objects, diagrams or graphs, concept connection maps, mathematical relationships or computer simulations. Models can be actual or conceptual, or combinations of both.

As science instruction progresses so, too, should students' ability to analyze and model more complex systems and to use a broader variety of representations to explicate their models. Students' thinking about systems in terms of component parts and their interactions is the initial step that provides a basis for building more sophisticated understanding of systems in terms of inputs, outputs and processes.

As students progress, their models should move beyond simple scale models or maps and begin to incorporate and make explicit for students invisible features of a system such as interactions, energy transfers or matter flows. Mathematical ideas such as ratio and simple graphs should be seen as tools for making more definitive models and eventually students' models should incorporate mathematical relationships among quantities, and some analysis of the patterns of those relationships.

Instruction should also include discussion of the interactions within a system. As students' understanding deepens they can move from a vague notion of interaction as one thing affecting another to more explicit realizations of physical, chemical and biological types of interactions and their importance within systems. Students' ideas about interactions in the system become more sophisticated in parallel with their understanding of the microscopic world (atoms, molecules, biological cells, microbes).

Models are also a tool students can use in explicating their own knowledge and clarifying their questions about a system. Student-developed models can reveal problems or progress in a student's conceptions of a system and hence can also provide teachers with formative evaluation information.

Energy and Matter: Flows, Cycles, and Conservation

Because of fundamental conservation laws, tracking energy and matter flows, into, out of, and within systems helps one understand their behavior.

The universe consists of space, matter and energy. Scientists examine, characterize and model the flow of energy and matter in space in order to understand how a system functions. The availability of energy and of each particular type of matter restricts the operation of any system or component within a system. Hence it is very informative to track the flows of matter and energy into, within, and out of the system under study. Tracking energy and matter flows helps understand what occurs and, equally important, what does not occur within the system. This is true whether the system is natural or designed.

One underlying reason that it is worthwhile to track these flows is to reinforce the recognition that energy and matter are conserved, although they may change form. Such conservation laws provide limits on what can occur in a system, for example without an input of energy (sunlight) and matter (carbon-dioxide and water) a plant cannot grow.

Within many systems there are cycles of various types. In some cases, the most readily observable cycling may be of matter, for example, water cycling between the earth's atmosphere and its surface and subsurface reservoirs.

Development of specific understanding of matter and energy are spelled out as core ideas 1 and 3 of the physical sciences (see the Prototype Learning Progressions). The cross-cutting concept here is that flows of matter and of energy occur in systems at all scales, and are an important element to examine and to describe in system modeling. The ability to examine, characterize, and model energy and matter flows or cycles is a tool that students can use across many areas of science and engineering. Examining interactions between matter cycles and energy flows requires and supports students to develop increasingly sophisticated conceptions of both matter and energy, and of their role in any system. Instruction should engage students in explaining phenomena in terms of matter, energy, and the underlying physical processes that cause transformations of either into different forms.

Form and Function

The way an object is shaped or structured determines many of its properties and functions.

"Form and function are complementary aspects of objects, organisms, and systems in the natural and designed world. The form or shape of an object or system is frequently related to its use, operation, or function. Function frequently relies on form. Understanding of form and function applies to different levels of organization. Function can be explained in terms of form and form can be explained in terms of function." (*NSES* and *Science College Board Standards for College Success*).

Form means shape or structure. At the smallest scale the substructure of matter determines its properties. Thus for macroscopic objects the word form as used here refers to the structure, shape, and the properties of materials in an object. The functioning of both natural and designed systems depends on the properties of the materials from which they are formed, as well as on the shapes and shape-relationships of certain key parts. A sense of scale is necessary in order to know what properties, and what aspects of shape or substructure, are relevant to consider in investigating particular phenomena. Many observable properties of materials can be usefully characterized at the macroscopic scale but are meaningless at the microscopic level. For example the viscosity of a liquid is meaningful if trying to understand how a fish can swim through it, but not if asking about how bacteria move through it.

In any system form and function can be examined at many scales; which scale is appropriate depends on the question being asked. For example, understanding how a bicycle works is best addressed by examining the forms and functions of the frame, wheels, pedals, gear cogs, etc. However, building a lighter bicycle may require an understanding of the properties (rigidity, hardness) needed for the materials for specific parts of the bicycle in order to seek less dense materials with the desired properties, and this leads one to examine the atomic scale structure of the materials to design new materials with the desired properties.

Exploration of the relationship between form and function can begin in early grades through investigation of concrete and visible systems in the natural and designed world. As children move through the elementary grades, they can progress to understanding relationships of form to mechanical function (bicycles, the bones in a skeleton), and of form at a microscopic level to properties of materials (particulate level ideas without explicit atomic models). By the middle grades, students can begin to visualize, model and apply their understanding of form and function to more complex or less easily observable systems (e.g., structure of water and salt molecules and solubility, structure of earth and plate tectonics).

As students develop their understanding of the relation between form and function, they can apply the idea to investigating phenomena that are unfamiliar to them. This is valuable because often the first step to deciphering how a system works is to examine in detail what it is made of and what shapes and forms its parts take. Likewise, in designing any mechanical system or any structure, relationships of form and function are critical elements in successful designs.

Stability and Change

For both designed and natural systems conditions of stability and what controls rates of change are critical elements to consider and understand.

"Much of science and mathematics has to do with understanding how change occurs in nature and in social and technological systems, and much of technology has to do with creating and controlling change. Constancy, often in the midst of change, is also the subject of intense study in science." (*Benchmarks for Science Literacy*).

Stability denotes a condition where some aspects of a system are constant or unchanging, at least at the scale of observation. Stability of a system can take different forms. The simplest is a static equilibrium, such as a ladder leaning on a wall. A system with constant conditions with steady inflows and outflows can be said to be in dynamic equilibrium. For example, a dam may be at a constant level with a steady flow of water in and out. Alter the flow, and a new equilibrium level will eventually be reached. A repeating pattern of cyclic change such as the moon orbiting the earth can also be seen as a stable situation, even though it is clearly not constant or static. However, such a system has constant aspects, such as the distance from the earth to the moon, or the period of its orbit.

In designing systems for stable operation the mechanisms of external controls and internal feedback and control systems are important design elements. Feedback is important to understand in natural systems as well. A feedback loop is any situation where a condition triggers something which causes a change in that same condition, such as the temperature of the room triggering the thermostatic control that turns on the room's heater. Feedback can stabilize a system (negative feedback –a cold room triggers heating) or destabilize it (positive feedback – melting ice causes running water which melts more ice). Feedback in designed systems is usually to increase stability, while in natural systems feedback loops can function either way.

A system can be stable on one time scale, but on a larger time scale it may be seen to be changing. For example, looking at a living organism over the course of a day it may maintain stability within a stable range of conditions (homeostasis), though over months or years the organism grows or ages. For larger systems, such as development of the variety of living species inhabiting the earth, or the formation of a galaxy, the time scales can be very long indeed; such processes occur over billions of years.

When looking at patterns of change over time it is as important to examine both what is stable or unchanging and what is changing about the system under study. Understanding the balance of processes and the feedback mechanisms that regulate stability or drive instability in the system provides insight into cause and effect and may facilitate prediction for its behavior.

Any system may have a range of conditions in which it can operate in a stable fashion, yet in other conditions it cannot function. For example, any living organism can live only within a particular range of temperatures, and outside that range it will die. Elucidating what range of conditions can lead to stable operation and what changes would destabilize a system and in what ways is an important goal for many system models. Stability is always a balance of competing effects, and a small change in conditions, or in a single component of the system, can sometimes lead to runaway changes in the system.

Students typically begin with an idea of balance (equilibrium) as a static situation, and interpret lack of change in the system as an indication that nothing is happening. They will need guidance to begin to understand that stability can be the result of competing, but balanced forces, and to identify and understand the invisible forces in a static situation.

Developing an understanding of dynamic equilibrium is crucial to understanding major issues in any complex systems, for example population dynamics in an ecosystem or the role of atmospheric carbon in climate change. It is equally important for achieving a consistent physical understanding of forces and energy within matter and how the amount of energy stored in matter changes, for example, due to the minute deformation of the table surface caused by the book lying upon it. Explicit and visible examples of how change in some factor produces changes in the system can help establish a mental model of dynamic equilibrium useful for thinking about more complex systems.

Understanding long term changes or evolution, for example of the structure in the universe, the surface of the Earth, or the diversity of species, and a sense of the requisite time scales for such changes to progress is an important aspect of modern science. Such long time scales can be difficult for students to grasp. Part of this understanding must grow from an appreciation of how scientists determine the time scales of these processes, from an interplay of evidence and system modeling.

TOPICS IN SCIENCE, ENGINEERING, TECHNOLOGY, AND SOCIETY

Science, engineering, and technology do not exist in isolation from society: they are a part of, contribute to, and are influenced by the society and culture in which they take place. Consideration of the historical, social, cultural, and ethical aspects of science and technology needs to be linked to other social science studies and raised in the science classroom. It is important for students to develop an understanding that the various disciplines of science, engineering, and technology are interrelated and share common rules of evidence to explain phenomena in the natural world. It is equally important for students to understand that science, engineering, and technology are human endeavors and as such may raise ethical issues that are not solved by science alone.

Students need opportunities to consider and discuss the applications and implications of science and engineering in society with increasing sophistication across the grade levels. Likewise they need developing awareness of the opportunities for careers and professions afforded by science, engineering and technology capabilities. In this section we develop a brief summary for each of a set of core ideas around connections between science, technology and society that should be addressed in the science classroom and linked to other studies of social issues.

History and Cultural Roles of Science, Engineering and Technology

One of the singular traits of humanity is the desire to explore and understand the world. Every culture develops understandings of its local environment and of the natural hazards and benefits that it affords. Each culture has developed its own suite of tools; building skills; agricultural knowledge (including selectively bred plants and animals for food); medicinal uses of local plants; and interpretations of the heavens, of cycles of weather, and of natural events. Science, too, is a particular form of cultural knowledge and its practices and assumptions are shaped by this cultural heritage.

The dominant forms of science and engineering emerged primarily in Europe at the dawn of the industrial revolution; however, they were, and continue to be, influenced and informed by appropriating and incorporating insights from many other cultures. Individuals from diverse cultures have contributed to mathematics, science, engineering and technology and their varied cultural insights and ways of thinking have advanced science and broadened the scope of technology. Increasing participation of women in science and engineering has broadened the vision of these professions as well.

Science and technology have their own histories, and the stories of how people made discoveries and invented tools and machines—as well as medicines and medical treatments—are a key element of science. For some students, it is one of the roots of their interest in science. Science and engineering are human endeavors and human intellectual achievements. Teaching science and engineering without reference to the rich variety of human stories, the puzzles of the past and how they were solved, isolates science from its human roots, undervalues the intellectual and creative contribution of science, and diminishes its interest for many students.

Impacts of Science, Engineering, and Technology on Society

Human lives have been profoundly altered by advances in science, engineering, and technology. Modern societies, especially cities, are dependent on engineered systems and technologies and on medical knowledge and practices for their very survival. This is not to say that science and engineering advances are automatically beneficial, their capabilities can also be used for destruction and can do damage. Indeed, over history, it was the development of weapons that drove much study and allowed societies possessing new technologies to dominate and even destroy those that did not. More broadly, humans have so successfully out-competed other species that the environmental effects of human actions on both local and global scales are important and pressing current societal issues.

Students need to develop an appreciation of how to think about both the benefits and risks offered by new science and new technologies. Classroom debate and discussion of choices related to new scientific or technical developments are important, and it is equally important that they are conducted with respect for a variety of opinions, as well as respect for the role of evidence in evaluating both risks and benefits. One of the important outcomes of classroom discussion is for students to recognize that scientific inquiry is characterized by a common set of values that include logical thinking, precision, open-mindedness, objectivity, skepticism, and honest and ethical reporting of findings.

Impact of Societal Norms and Values on the Practices of Science and Engineering

Scientists and engineers do not operate in a vacuum. They are part of societies and their approaches, attitudes and values generally reflect those of the society in which they live which increasingly today, is a global society with global concerns. Scientists are also members of specific cultural groups that shape their values, attitudes, and approaches. This fact can shape the research priorities and assumptions of science and engineering and has a tendency to exclude the perspectives of groups that have been historically marginalized. The quality of science and engineering can be improved through efforts to make the endeavor more inclusive of members across the range of cultural groups in society.

Society has a role in deciding what avenues in science and engineering to support and pursue and what to regulate or even proscribe. Decisions are made at the local, national and international levels. Every citizen has a right and responsibility to participate in this decision making; it is not the domain of scientists and engineers alone. However, scientists and engineers, because of their expertise, have particular responsibilities: first to ensure that the debate is informed by the best understanding available of the issue at hand; and second, to abide by societal decisions once they are made. Such decisions include environmental, health and safety regulations on both research and on engineered systems as well as, more rarely, proscriptions on, or security classification of research and development in particular areas. It is important for students to understand that science and technology may raise ethical issues which science and technology alone cannot address adequately.

Professional Responsibilities of Scientists and Engineers

Science and engineering, like every profession, have internal ethics and responsibilities. For scientists, responsibilities to science and to the broader community include honest reporting of results and information, evaluation and reporting of uncertainties and risks, informing policy decisions in responsible ways, engaging in the process of argumentation and critique that is key to developing scientific theories, and recognizing both honest mistakes and fraudulent results. For engineering, there are further responsibilities to ensure that the technologies, devices and treatments that are developed take into account and support individual and public safety, as well as meeting their designed purposes effectively and efficiently.

Of course, professional science and engineering are carried out by a diverse group of individuals who bring a range of motivations and value systems to their work. Classroom discourse can help students distinguish between professional norms and individual behaviors.

Some discussion of these aspects of science-related careers has a place in the science classroom, both because it provides a backdrop for evaluating input in public discourse from a variety of sources, and because these aspects of careers can be part of what draw student interest to them. If the students' image of the scientist or engineer is that of an amoral expert (or worse yet the grinning evil scientist stereotype from horror movies), they are much less likely to identify with the possibility of becoming such a person than if they see sciences and engineering as professions that strive for ethical and moral outcomes in addressing real world problems as well as for knowledge and products.

Roles of Scientific and Technical Knowledge in Personal Decisions.

Science is a way of knowing that is used by many people, not just scientists and engineers. Individuals make decisions every day that affect their health and safety, their use of technologies, and their impact on the environment. They also make decisions about local and national issues that affect their community. Many of these decisions relate to issues informed by science and affected by engineering and technology. No one person can be an expert on all the issues that might affect his or her life, but each can make better decisions if they understand how to gather and interpret relevant scientific information, explore alternative solutions effectively, and deal with issues of probability and risk in an informed way. Of course these are not the only things that influence personal decisions; culture and values play important roles. Nevertheless, the ability to recognize what kind of evidence is used to support an argument, and to be aware of multiple elements of complex and technical issues must be developed in the science classroom, as well as in other parts of a student's education. Recent educational research highlights the importance of helping students create a science-linked identity in order to better support a sustained, lifelong engagement with science. Students who see themselves as science oriented and science capable are more likely to feel confident to consider scientific inputs as important to their personal decision making.

Careers and Professions Related to Science and Engineering.

Because so many aspects of life today are touched by science-based technologies and approaches, the range and variety of careers that use and involve scientific or engineering knowledge is very broad. Specific careers exist for all levels of education from technicians with certification or community college degrees to those with multiple years of post-baccalaureate study, such as research scientists, doctors and professional engineers.

Throughout their science education students need to be exposed to the variety of such career and professional options and to become informed about the educational pathways and programs of study that open these careers to them not only within science but other careers external to science where science qualifications are valued . This is particularly important for students who have limited access to this knowledge in their home and community environments. Educational standards can also help ensure that similar educational and career-goal expectations and rich opportunities to learn are in place for all students.

Students’ interest in careers in science or engineering has been found to correlate with their early interest and motivation for studying science. Multiple examples show that students’ motivation for studying science can change dramatically when they see the linkages between the science they are learning in school and the ability to do interesting work, to play a useful role in the world, as well as to be employed. Thus, the rationale for pursuing a career in science can include an understanding of both the personal and societal benefits.

Chapter 5

Dimension 3: Scientific and Engineering Practices

From its inception, one focus of science education has been to develop scientific habits of mind such as the critical spirit which is the hallmark of the scientist, an understanding of the approach to scientific inquiry, and how to reason in a scientific context. Nevertheless, the production of curricula that provide a coherent account of science and of the range of practices that support and enable the construction of reliable knowledge has been a challenge. The intent of Dimension 3, therefore, is to provide a guide that would give science and engineering practices a more comprehensive realization and a more central place in the next generation of science standards, curricula and assessment. Engineering practices are included in keeping with our view that science and engineering are both elements of the framework. In some cases, the practices of science and of engineering overlap; however, in those cases where they are distinct from each other we discuss each separately.

Just as it is impossible to appreciate what makes *The Adventures of Huckleberry Finn* one of the great American novels without engaging in a critical analysis of the text, it is impossible to comprehend why the explanatory theories that science offers and the technical solutions developed by engineers are profound intellectual and creative achievements without some understanding of the norms, values, and critical practices of these communities. In the case of science, this requires an understanding of *how* scientific knowledge relates to other events, *why* it is important, and *how* this particular view of the world came to be. In the case of engineering, students need to see *how* humankind has used scientific and technical knowledge to address the challenges that confront us. The insights gained from studying and engaging in the practices of science and engineering can help students recognize that the work of scientists and engineers is a creative endeavor, and one that has the potential to contribute to solving major challenges that confront society today, such as generating sufficient energy, preventing and treating disease, maintaining supplies of fresh water and food, and meeting the challenges of climate change. Any science education which focuses predominantly on the detailed products of our scientific labor – the 'facts' of science – without developing an understanding of how those facts were established, or which ignores the many important applications of science in the world, misrepresents science and marginalizes the importance of engineering.

HOW SCIENTISTS AND ENGINEERS WORK

Scientists and engineers draw on an extensive body of knowledge about the natural world, including fundamental theories, laws, and facts. They think in terms of systems, and build models to understand how the relevant systems function and change. Commonly scientists and engineers work together in teams. While the goal of science is to create new knowledge of the material world, the goal of engineering is to develop new solutions to technological problems. Some of the relevant practices for engineering are quite different from science, while others – such as the need to research and to engage in constructive critique – are quite similar. Neither science nor engineering can be described by a linear process that follows a well-defined path. Individual engineers and scientists may take very different paths as they pursue different questions or solve different problems. Each, however, uses an iterative cycle of development, testing and refinement, whether it be of ideas or of designs.

The practice of engineering often involves applying scientific concepts; indeed, the line between applied science and engineering is difficult to draw, which is one reason why we take the position that engineering is integral to K-12 science instruction. It also involves the flexible and creative use of practices such as defining problems, considering tradeoffs, building and testing models, and optimization. Engaging students in the practices of engineering alongside the practices of science will provide them an opportunity to learn how to use science to solve real problems, in their own lives and in the wider society. This is an additional reason for presenting engineering practices as an integral element of this framework.

Indeed, the practices of science and engineering are deeply intertwined. The need to solve problems has led to the development of technologies that have spurred scientific advances; and the need to answer questions about the natural world, as well as the answers to those questions, have driven the development of new technologies. This relationship between science and engineering has become more interdependent over time, so that today it is impossible to do science without the products of engineering, or to do engineering without knowledge of science.

Investigation, Hypothesis, and Coordination

One way of understanding the work of scientists and engineers is to frame their activities as consisting of work that is done in three areas. Broadly these may be conceived of as one space where the dominant activity is investigation and empirical inquiry, a second space where the essence of work is the construction of hypotheses, models or prototype designs, and a third coordination space where the ideas such as the fit of data to predictions, or the appropriateness of experimental or product designs are debated and evaluated.

In the investigation space, scientists are engaged in the process of observing natural phenomena, planning experiments or programs of observation and data collection, building instruments, determining what needs to be measured, engaging in disciplined fieldwork, and identifying sources of uncertainty. Similarly, engineers investigate the designed world, collecting data to evaluate the strengths and weaknesses of a particular design solution.

In the hypothesis space, scientists and engineers develop their theories, designs and models, and consider alternative explanations. Here scientists construct explanatory models of the material world, and engineers develop and redefine possible solutions to technological problems.

The coordination space is where work in the investigation space – impirical enquiry – is related to the practices of constructing theories and models and making predictions, or of proposing design solutions. The dominant practices here are analysis, argument, and critique. Whether it is new theories, novel ways of collecting data, or fresh interpretations of old evidence, scientists use evidence-based argumentation to make their case for new ideas. In response, other scientists attempt to identify weaknesses and limitations. This critical process is key to advancing scientific knowledge and understanding. Engineers use this space in a similar manner, mediating between practical activity (in the investigation space), their knowledge of scientific theories, models for how the theories apply, and the creative solutions that they generate (in hypothesis space.) by analysis, argument, and critique. The coordination space is where engineering practice meets the need for critical dialogue among engineers and with other stakeholders. It is here that models and designs are examined critically to consider possible risks, to see if they meet regulatory requirements, and to evaluate and respond to societal input on newly engineered approaches to a problem.

Both scientists and engineers must move recursively in a fluid, dynamic and unconscious manner across all three of these areas—between the real world, the world of their ideas, and their critical evaluation—to see how well they can explain a phenomenon, or solve a problem. From an educational perspective, these domains offer a means for identifying the range and variety of scientific practices and for ensuring that any framework offers a valid and balanced picture of their variety and importance.

Models

One of the creative engines that drives the scientific and engineering enterprise is the creation of models. Models take many forms, any of which is an abstract representation of some system in the material world. Scientists and engineers develop both representational models and mental models of the system they are investigating or designing. The term representational model is used here to mean any combination of picture or diagram, physical model, mathematical model, or computer simulation which aids the scientist or engineer in developing an understanding of the issue they are investigating or of the solution to a design problem they are facing. Their relation to the physical world is akin to the relation between a map and the landscape it represents.

Mental models are the way the scientist, engineer or student internalizes their understanding of scientific theory and its application to the system at hand. They are refined with the aid of representational models and through discourse with others. Such models are then used in predicting outcomes or generating new ideas and refining theories. A large part of science instruction, therefore, is about helping students progressively refine and develop their mental models so that they eventually accord ever better with established scientific theories and understandings. Students are then able to draw on these models as they interpret new situations or solve new problems. Developing and using representational models is a key step in refining mental models and is therefore, an important practice in both science and engineering, and in any education in science and engineering.

Communication and Discourse

Another key feature of the work of scientists and engineers is scientific communication, which includes the practices of reading scientific reports, constructing written articles, and engaging in deliberative discourse with others. Researchers have demonstrated the centrality of reading to the practice of science, showing that, on average, scientists read for 553 hours per year or 23% of total work time. When the activities of speaking and writing are included as well, the scientists in their study spent on average 58% of their total working time in communication or working in the coordination space. More importantly, scientists and engineers were found to consider reading as essential to their work and as their primary source of creative stimulation. Thus the dominant practice in science and engineering is not 'hands-on' manipulation of the material world but rather a 'minds-on' social and cognitive engagement with ideas, evidence and argument. Reading, for instance, is an act of inquiry into meaning – an attempt to construct sense from the multiple forms of representation used in science – words, symbols, mathematics, charts, graphs and visualizations. Each individual must engage in a process of using his or her existing knowledge to interpret text and generate new understandings. Hence, a vital and important role for any education in the sciences and engineering is to explore how words and symbols are used to construct specific scientific meanings.

Being a critical consumer of the sciences and the products of engineering, either as a lay citizen or a practicing scientist or engineer, requires the ability to read scientific or scientifically related texts and recognize the salient science; to identify sources of uncertainty and methodological flaws; and to distinguish observations from inferences, arguments from explanations, and claims from evidence. Judging the validity of knowledge claims also requires knowledge to be contextualized in its socio-historical context with new knowledge claims examined in the light of previous research and the potential biases of the researcher(s).

Peer review is the formal articulation of this practice by the scientific community. Over time, ideas that survive critical examination attain consensual acceptance in the community and, thus, through discourse and argument, science maintains its objectivity. Critique is not, therefore, some peripheral feature of science. Rather, it is core to the practice of science and without it the construction of reliable knowledge would be impossible. Whether it is the theoretician who is developing a theory to explain a phenomenon, the experimentalist who is proposing new ways of collecting data, or the engineer offering a new design, all must subject their ideas to the scrutiny of their peers.

Historically, formal science education has overemphasized the activities and practices that scientists conduct in the investigation space, such as the collection of evidence, at the expense of the activities of model building, hypothesis generation, and the coordination of theory with evidence. Students need to emerge from their education in science with an understanding that, while the practices of observation and experiment provide a foundation from which science is built, building the explanatory ideas or theories, the edifice of science, requires engaging in the broader practices of analysis, synthesis and critique. In addition, an overemphasis on the laboratory aspects of science minimizes the fact that scientists and engineers are always part of a wider social environment, which has strongly shaped their knowledge, skills, resources, motives, and attitudes.

PRACTICES FOR SCIENCE CLASSROOMS

The description of how scientists and engineers work in three areas provides some insight into the practices of science. Drawing on this notion, we now highlight what we see as a set of essential practices as core for any education in the sciences and engineering. Each is first summarized briefly to give a sense of the full range of practices to be considered. Then we expand on each of them in Tables 1-16 that follow to show how students might engage in each practice in increasingly sophisticated ways to develop their knowledge, understanding and skill with each practice.

We have not attempted to map the levels of sophistication with particular grade levels for two reasons. First, there is limited empirical evidence on which to base such judgments. Second, it seems likely that students' ability to engage in more sophisticated practices might be tied less to a particular grade level and more to their familiarity with a particular topic or the previous opportunities they have had to engage in these practices.

Asking Questions

Questions are the engine that drives science and engineering. Science, itself, seeks to answer three questions:

- What exists and what happens? (the ontological question)
- Why does it happen? (the causal question)
- How do we know? (the epistemic question)

The focus of engineering, in contrast, is the question of:

- What can we do with such knowledge? (the technological question)

While both science and engineering share the need to consider the question of:

- How do we talk about phenomena evidence and explanations? (The communicative question)

The skill of questioning is also essential to the process of engaging in argument and critique, helping to identifying errors and weaknesses in arguments. Asking questions is the foundation of creative and higher order thinking and an essential part of the scientific habits of mind. Hence, the facility to ask good questions is an excellent test of deep comprehension.

All inquiry in science and engineering begins with, and is driven by a question or questions. Questions initiate the development of hypotheses and the construction of models. Thus, the experience of learning science and engineering should develop the ability to ask questions which can be answered either empirically or practically. Students also need to recognize the distinction between questions that are answerable empirically and those which are only answerable within other domains of knowledge or human experience. The ability to ask questions of others is also key to the kind of critical discourse that the scientist and engineer conduct in the coordination space and central to constructing deeper understanding. Table 1 provides our view of the kinds of performances we might expect of students as their knowledge and understanding develops.

Table 1: Asking Questions

Beginning	*Emerging*	*Competent*	*Proficient*
Asks questions about the material world e.g. Why is the sky blue? Where does the sun go at night? What do bees do?	Distinguishes a scientific from a non-scientific question	Asks questions which can be answered empirically or practically within a science/engineering classroom and uses these to design an inquiry or construct a pragmatic solution.	Asks critical questions which seek to identify the premises of an argument, requests further elaboration or challenges the interpretation of a data set e.g. how do you know? What evidence supports that argument?

Modeling

Having formulated a question that can be empirically investigated, the scientist commonly moves to the process of seeking answers by working in the hypothesis space, developing models that represent the system in question and framing specific hypotheses about the aspects of the system that the question seeks to probe. Understanding the material world requires that scientists go beyond observables and imagine a world not yet seen, modeling it as it might be. Models enable prediction of the form "if…then…therefore" and provide a possible causal explanation for answering questions. Engineers likewise build models or prototypes to test their designs. In science education, a range of models are essential to building student understanding. Biology teachers help students visualize the cell with physical models or by using an analogy of a city where the nucleus is the city hall, the mitochondria the power plant and so on. Chemistry teachers use molecular models to explain the physical properties of certain substances while physics teachers develop mathematical models to explain the behavior of gases. Indeed, it is impossible to engage in science or engineering without the practice of constructing models. To date, within science education, there has often been only been tacit recognition of this core practice.

Through their experiences of learning any or all of the sciences or engineering, students need to develop an understanding that scientists and engineers use a range of means to construct representations of the material world. Many of these representations are akin to maps in that they do not correspond exactly with the world but bring certain features into focus and enable predictions and causal reasoning. Thus, scientists build models of phenomena and the real world in their work, from simple models of the cell or human body to highly complex computer models of the atmosphere. Engineers commonly build models with computers or physical prototypes to test their designs (Table 2).

Table 2: Modeling: How do scientists and engineers build pictures of the World? (Constructing Representations of the World)

Beginning	*Emerging*	*Competent*	*Proficient*
Constructs drawing or representations of events e.g., draws a picture of an insect or represents what happens to the water in a puddle as it is warmed by the sun or builds a simple physical model of a real-world object	Constructs a model using analogy, representations or metaphor as an aid to explanation or as a means of communicating understanding. Makes modifications to improve detail or clarity.	Represents phenomena with more than one model. Students revise their models to better fit the available evidence.	Uses models to generate questions about a phenomenon. Evaluates models to improve their quality or explanatory power.

Through the construction and use of models and representations in learning any of the sciences or engineering, an understanding and knowledge needs to develop that models and representations are the foundations of scientific theories and essential to the practice of science and engineering. In science, these enable the development of conjectures (hypotheses) about the world which are empirically testable and the construction of causal explanations. In engineering, they enable more accurate prediction of how systems will behave (Table 3) and guide refinement of designs.

Table 3: Modeling: What is the role of models? (Using Models to Make Predictions)

Beginning	*Emerging*	*Competent*	*Proficient*
Students use representations, analogy or metaphor to talk about phenomena	Students use models as a means of talking about what might happen if one element is changed.	Students use their models to make predictions and to explain phenomena.	Students use models to make testable predictions

Mathematics is a central and integral feature of science and engineering which is used for constructing theories and models. Mathematics enables the numerical representation of variables and their relationships, the symbolic representation of physical entities, the development of explicit theoretical accounts of the physical world, and the prediction of possible outcomes Developing student familiarity with the role and use of mathematics in science is central to develop a deeper understanding of how science works (Table 4).

Table 4: Modeling: Why is mathematics a feature of science and engineering? (The Role of Mathematics)

Beginning	*Emerging*	*Competent*	*Proficient*
Uses numbers to represent a physical quantity.	Uses algebra to represent relationships among physical	Manipulates algebraic relationships to determine physical	Uses algebra, statistics and calculus as a means of expressing patterns

	quantities.	quantities.	and relationships in the physical world.

Devising Testable Hypotheses

Hypotheses structure an investigation because they frame a possible answer to the question that can be tested. Hypotheses both emerge from specific theories and models and extend them. Hypotheses go beyond prediction in that they develop a reasoned argument based on features of a theory or model, justifying the prediction and making explicit what aspect of the ideas are being tested. The equivalent engineering practice is proposing prototype designs for a solution to an engineering problem. In each case, the scientist or engineer must draw on their existing understanding to construct models that lead to a hypothesis or design proposal.

A hypothesis is not a random guess, nor is a design proposal. Each is based on established science and is directed to defining an investigation that will improve our ability to answer a specific question or refine a specific design. For students, framing an investigable hypothesis grounded in their existing scientific knowledge is, therefore, an essential precursor to any cycle of inquiry. Even a simple demonstration becomes a more meaningful learning experience when students are asked to form hypotheses and make predictions, and to justify them from their prior knowledge, before undertaking the activity or viewing the demonstration.

Table 5: Hypotheses: What they are and how do scientists use them?

Beginning	*Emerging*	*Competent*	*Proficient*
Offers a possible explanation in answer to a question and gives a reason for it.	Uses a simple model of the system in question and refers to it in constructing a hypotheses that	Constructs a hypothesis about how a model must be changed or extended to answer the question	Uses scientific knowledge and models flexibly and appropriately in constructing testable

	suggests how the system will behave and a reason behind that prediction.	and suggests activities that could test the hypothesis.	hypotheses and suggesting appropriate tests.

Collecting, Analyzing, and Interpreting Data

Answering questions and testing hypotheses about the material world is reliant on the systematic collection of evidence. Both laboratory experiments and detailed, structured field observations require measurements, data-collections tools, data records and data analysis. This is the work that is conducted in the investigation space. Measurement is vital to science and engineering as quantitative data enables patterns and features to be identified and represented. Students need, therefore, opportunities to learn how to select or construct instruments for the purpose of data collection that are appropriate to the needs of their inquiry. Students also need to see that the laboratory is not the sole domain for legitimate scientific inquiry and that, for many scientists e.g. earth scientists and ecologists, the ‘laboratory’ is the natural world. Engineers too must investigate the function and impacts of their designs both in the test laboratory and in the field.

Table 6: Collecting, Analyzing, and Interpreting Evidence: What measurements are needed? (Selecting Instruments)

Beginning	*Emerging*	*Competent*	*Proficient*
Recognizes the need to observe, record and measure. Uses simple tools such as rulers, magnifying	Selects an instrument appropriate to measure the required data.	Selects and uses an appropriate instrument to produce a data set, with justification	Identifies the appropriate instrument to measure a given quantity from alternatives and uses it appropriately with

glasses.			precision and skill.

In addition, students need opportunities to develop the skill of being able to estimate order of magnitude quantities that are reasonable and appropriate to the context. They should also be able to judge whether the data or answer to a problem is reasonable given the context. Table 7 shows the kind of performance that might be expected as their knowledge and skill develops.

Table 7: Collecting, Analyzing, and Interpreting Evidence: Are measurements correct? (Estimating Quantities)

Beginning	*Emerging*	*Competent*	*Proficient*
Compares estimates for weight, length and time with measured values	Estimates mass, length and time within an order of magnitude	Estimates a wider range of quantities to more than an order of magnitude precision	Estimates quantities to less than an order of magnitude precision and uses this skill to judge whether the evidence or an answer to a problem is reasonable.

Designing experiments requires the practice of identifying and controlling variables. The experience of learning science and engineering should, therefore develop the ability to identify the relevant variables, distinguish the independent from the dependent variables, and control variables where necessary.

Table 8: Collecting, Analyzing, and Interpreting Evidence: What varies and what should be varied? (Identifying and Controlling Variables)

Beginning	*Emerging*	*Competent*	*Proficient*

Identifies factors that vary in the situation under study	Distinguishes independent variables from dependent variables	Identifies ways to control all variables except one	For multivariate investigations, varies only one variable at a time while keeping all others constant Justifies which variable should be varied.

In learning science and engineering, students' experiences should develop the knowledge and skill to identify sources of error in any measurement e.g., systematic and random, and the standard methods that are used for their reduction (see Table 9).

Table 9: Collecting, Analyzing, and Interpreting Evidence: What procedures can be used to reduce error and uncertainty? (Reducing uncertainties, increasing precision)

Beginning	*Emerging*	*Competent*	*Proficient*
Recognizes that measurement can be subject to error	Identifies likely sources of error or inaccuracy.	Explains the significance of basic techniques for reducing uncertainties such as increasing sample size, repeating measurements and averaging Explains what aspects of the measurement could be improved with higher precision tools or by increasing sample size.	Identifies sources of error in measurement. Distinguishes between random effects and statistical uncertainties and systematic error. Explains how sources of error were addressed.

Once collected, data must be represented in a form that is communicable. Scientists and engineers tabulate, graph or chart data to help recognize its major features. Such data sets can be used to identify significant correlations that then enable the recognition of causal mechanisms. The practice of identifying relationships and patterns is central to science. Opportunities to examine data sets, both those students themselves have produced and archival data collected by others, and identify how they co-vary is therefore an essential for students. The identification of relationships is aided by the use of a range of tools including mathematics, charts and tables. Table 10 presents how this practice might develop with time.

Table 10: Collecting, Analyzing, and Interpreting Evidence: What patterns are there in the data? (Identifying Relationships)

Beginning	*Emerging*	*Competent*	*Proficient*
Describes what was done and records observations, e.g., drawing, writing, measurement.	Tabulates and represents evidence in a graphical form and looks for patterns. Can interpret simple data presented graphically (pie charts, simple graphs)patterns	Identifies patterns and relationships in data sets, including those with multiple variables	Identify patterns in more complex data and notes any anomalies. Explains why specific elements of data may be anomalous.

Large data sets are analyzed using well-established statistical techniques that aid the process of analysis. There is much useful science and science learning that can be undertaken with archival data sets – that is with data collected by others. Students, therefore, need to be able to identify relevant existing data sets for a question of interest, e.g., air pollution, seismic data, and CO_2 in the atmosphere, and conduct a range of analyses and interpretations of such data sets. See Table 11.

Table 11: Collecting, Analyzing, and Interpreting Evidence: What other relevant sources of data are there? (Using Archival Sources)

Beginning	*Emerging*	*Competent*	*Proficient*
Recognizes that data is	Identifies sources of	Accesses archival data	Seeks, analyzes and

collected by scientists and engineers in investigations.	data that may be relevant to an issue. Actively seeks existing data when investigating a question.	sets such as those available for weather, air pollution, seismic activity, and CO2 in the atmosphere and uses them to support arguments.	interprets the importance of archival data sets competently. Asks appropriate questions about the reliability and accuracy of archival data.

Constructing and Critiquing Arguments

Whether about new theories, novel solutions to technological problems, or fresh interpretations of old data, reasoning and argumentation are the practices that scientists and engineers use to make their case for new ideas. In response, other scientists and engineers attempt to identify weaknesses and limitations. In the sciences, reasoning and argumentation happen informally in lab meetings and symposia and formally in peer review. Over time, ideas that survive critical examination attain consensual acceptance within the community, and by discourse and argument science maintains its objectivity. Such activity is therefore a core practice of science. Similar processes are equally important within the engineering community in analyzing and evaluating strengths and weaknesses of a design solution, and particularly in optimizing solutions.

The production of scientific knowledge or new technological solutions is dependent on a process of reasoning that requires making a justified claim about the world. Arguments can be either deductions about the world from premises; inductive generalizations about what patterns may exist; or inferences to the best explanation. Developing an understanding of science and the origin of scientific explanations requires students to experience and use all of these forms of argument in the construction of knowledge. Likewise, engineering solutions must be argued for, and such arguments may encompass an analysis of multiple factors of risk, cost/benefit and aesthetics or functionality. Optimization of designs requires likewise a process of critique and argumentation. The study of science or engineering needs to develop a sense of the depth of thought and argument necessary to advance and defend a new idea or design. Thus students need to construct and defend their explanations, the interpretations that they offer based on data or the solutions they propose. In this sense, learning to argue is seen as a core process that supports learning to think and constructing new understandings. Comprehending why a wrong idea is wrong or what aspects make a design inferior matters as much as understanding why the right idea is right, or why the chosen design is optimal.

Table 12: Constructing Explanations and Critiquing Arguments: Why is argument a feature of science and engineering? (Constructing and Defending Arguments)

Beginning	*Emerging*	*Competent*	*Proficient*
Makes a claim and supports the claim with a reason.	Recognizes that science requires evidence to support its arguments. Advances claims which are supported by both evidence and reasons	Constructs arguments which are supported by empirical rather than personal data and warrants, and defends arguments with reasoning when questioned.	In response to criticism, identifies flaws in own arguments and modifies and improves the arguments.

Students also need the opportunity to experience the fact that any given set of data can be interpreted in different ways leading to different conclusions or that different models will lead to different predictions. Deciding upon which is better requires the experience of evaluating the merits of competing arguments, identifying the premises of an argument, and using counter-arguments to test the validity of any argument under a range of circumstances. Offering up new theories, tentative explanations or new models for critical inspection by others is a key process in constructing reliable explanations of the material world. See Table 13.

Table 13: Constructing Explanations and Critiquing Arguments: Why do scientists and engineers engage in criticism and debate? (Critiquing Arguments)

Beginning	*Emerging*	*Competent*	*Proficient*
Provides justifications for own claims Asks for justifications of others' claims	Recognizes that claims can be shown to be false or ideas weak by the use of evidence	Identifies weaknesses in the arguments of others.	Uses reasoning and evidence to construct a rebuttal or a counter argument to someone else's argument. Comprehends that modeling and argumentation leads to the development of scientific theories or better solutions to problems. Uses theory-based models to offer coherent explanatory accounts of the physical world, can identify criteria that have been used to judge their success, and identifies how other arguments were flawed.

Communicating and Interpreting Scientific and Technical Texts

Being literate in science and engineering requires the ability to construct meaning from informational texts. Like all disciplines, science and engineering are a way of knowing where whatever is known is communicated through the symbols (mostly words and mathematical expressions) in which the knowledge is codified. Reading and interpreting those texts is a fundamental practice of science. Any education in science or engineering needs, therefore, to develop students' ability to read and to produce written text. And, just as it is impossible to learn a language without engaging in its oral production, learning such a technical practice requires significant opportunities to talk the language of science and engineering, to write in its standard genres, and to listen to others using such linguistic forms. As such every science or engineering lesson is a language lesson. We, therefore, welcome the fact that the new draft standards for literacy have recognized that school science is an arena for developing students' facility with language – particularly the ability to read and produce the genres of texts that are intrinsic to science and engineering such as expository text and the experimental report. We also acknowledge that mathematics is essential to the practice of science and engineering, and that mathematical symbolism and techniques are vital to the process of representing and analyzing evidence, constructing models and simulations, and expressing causal relationships, and a frequent component of scientific text.

Through their learning in science, and through practice, students need to develop the skill and ability to construct meaning from scientific text either from textbooks, media reports or original papers. As a written form, science text is challenging. It is expository rather than narrative and is often linguistically dense and reliant on multiple and specific logical connectives. Hence the ability to read scientific text can only be developed through sustained practice and support. Fluency with scientific texts will only develop through practice at both reading scientific text (constructing and interpreting meaning), writing scientific text where language is used to express scientific ideas and thinking, and opportunities to engage in extended discussion and oral presentation about scientific ideas. See Table 14 and 15.

Table 14: Communicating and Interpreting Science: Why is reading such and important practice in science? (Reading Science)

Beginning	*Emerging*	*Competent*	*Proficient*
Identifies the main topic, focus and key details of a scientific or technical text.	Knows and uses various text features (e.g., captions, headings, tables of contents, glossaries, indexes, electronic menus, icons) to locate key facts or information. Explain how images and illustrations contribute to and clarify a text Asks about the reliability of a source	Reads informational texts independently, proficiently, and fluently within the level of complexity appropriate for one's age Can explain how an author uses evidence to support his or her claims in a text, and identify what evidence supports which claim(s) Uses appropriate criteria both from within the text and in relation to the source of the text to judge if it is likely to be scientifically reliable.	Reads and interprets multiple sources in researching a science question. Analyzes and summarizes in detail the main ideas in a text and their implications. Compares and contrasts arguments from different sources and combines information from them when it is consistent.

Table 15: Communicating and Interpreting Science: Why do scientists need to write? (Writing Science)

Beginning	*Emerging*	*Competent*	*Proficient*
Uses notebooks to record observations and thoughts.	Writes informative or explanatory texts that are either reports of a phenomenon, recounts of investigations or procedures for conducting a task. Uses writing about models and diagrams to articulate his or her	Writes either: explanatory texts, reports or design briefs using relevant facts which lead to a conclusion Or	Writes explanatory texts, reports and argumentative texts of increasing detail and sophistication. Produces coherent and detailed reports of any inquiry based activity using primary or secondary evidence.

	understanding of a topic and construct questions Begins to write and present material for a diversity of audiences.	Argumentative texts that draw on evidence to justify one explanation over another of a specific course of action.	Uses writing in combination with diagrams and models to explicate and refine thinking about a topic.

Applying and Using Scientific Knowledge

Science does not exist in a vacuum, rather it interacts with society and technology in multiple ways. Technological problems have led to scientific advances and scientific advances are often dependent on technological advances. For many, if not most students, the meaning and relevance of the discipline lies in its potential contribution to creating new artifacts and generating solutions to the problems of society. Engineering is a disciplined process of using resources and human creativity to achieve human purposes by creating and applying technologies. Understanding science is important in developing technological solutions but in their evaluation multiple criteria of an economic, social, cultural and ethical nature must be considered. The practices that are essential to this domain require the ability to analyze systems, identify problems needing technological solutions, and develop, construct and evaluate solutions.

Classroom opportunities for students to apply their scientific knowledge and develop their knowledge and understanding of the practices of engineering serve multiple functions; they aid students' understanding both of science and of the technologically-dominated world in which they live. Other opportunities for applying and using scientific knowledge occur at the interface between science and social science, where the practices of constructing and critiquing arguments are applied to discourse around societal problems and the role of science and engineering in understanding and addressing them. Students need opportunities to engage in such discourse in their science classroom. Classroom practices specific to engineering design as a problem solving approach are exemplified in Table 16.

Table 16: Applying and Using Scientific Knowledge: What engineering approaches contribute to developing engineered solutions to problems? (Developing, constructing and evaluating solutions, using systems thinking.)

Developing Solutions			
Beginning	*Emerging*	*Competent*	*Proficient*
Identifies a problem that can be solved by the application of simple technologies.	Designs or proposes a technological solution to a simple problem	Builds a physical model or simulation of a technological system.	Works collaboratively as part of a team with distributed expertise to develop a designed solution to a problem drawing on range of disciplinary knowledge.
Constructing Solutions			
Builds a structure with two different materials to determine which is the most effective solution.	Builds a model and adapts the model to better solve the problem	Builds and tests a prototype to the point of failure. Analyses the failure to identify flaws in the model or erroneous assumptions.	Recognizes the need to design and test alternative solutions and mathematical simulations, and identifies the kind of knowledge needed to develop a solution.
Evaluating Solutions			
Explains why one solution is better than another.	Identifies the criteria necessary to judge a technological solution	Evaluates or considers the implications of a possible technology or application.	Evaluates competing solutions and is able to justify the choice of one and the reasons for its selection.
Using Systems Thinking			
Recognizes that made objects have been designed to meet a specific need.	Identifies the elements of a technological system	Recognizes that technological solutions have resource, societal and ethical implications that are design constraints. Identifies feedback and control elements of a system and can describe their function	Identifies the range of factors – social, resource, regulatory, ethical and risk that affect the design process.

Chapter 6

Putting the Dimensions Together: Performance Expectations

This framework is intended to guide the development of standards, curriculum, and assessments for science, as well as to provide perspectives for science teachers to guide their instructional planning and classroom activities. The Framework is designed to help realize a vision for science and engineering education in which students actively engage in science and engineering practices in order to deepen their understanding of core ideas in science over multiple years of school. In this vision, cross-cutting concepts serve as linkages that unify and inform science learning across units or courses focused on particular core disciplinary ideas. The committee recognizes, however, that integrating the framework's three dimensions in a coherent way is challenging and examples of how this integration can be achieved are necessary. One way of illustrating how the three dimensions can be brought together is through articulation of performance expectations for students.

The term performance expectation is used for statements that describe activities and outcomes which students can be expected to achieve as a means to demonstrate their ability to understand and apply the knowledge described in the content statements. Such performance expectations are a vehicle to specify what we expect students to know, understand and do, and how they can demonstrate that knowledge; these in turn serve to guide the design and development of both instruction and assessment. Following the model of the College Board *Standards for College Success* we agree that "Performance expectations specify what students should know, understand and be able to do….. They also illustrate how students engage in science practices to develop a better understanding of the essential knowledge. These expectations support targeted instruction and assessment by providing tasks that are measureable and observable." (College Board, 2009).

ILLUSTRATIONS OF PERFORMANCE EXPECTATIONS

To illustrate what we mean by performance expectations, most especially how they reflect the integration of core disciplinary ideas (Dimension 1) and science and engineering practices (Dimension 3), we are providing two sets of examples for specific components of the elaborated grade-level content specified in the prototype learning progressions for Life Sciences and Physical Sciences (see Chapter 7: Prototype Learning Progressions). Similar examples could also be generated for the content described in the progressions for Earth and Space Sciences, and Engineering and Technology. Almost any assessed topic can also be linked to one of the cross-cutting ideas (Dimension 2), and these linkages should be made in instruction. However, it is difficult to make explicit linkage to these ideas as well as to the other two dimensions in every performance expectation.

For the case of Life Sciences (see Table 1), we have chosen a Core Idea (LS1 -- Organisms: Processes and Structures), a Component Idea (LS1.C -- Organization for Matter and Energy Flow in Organisms) and selected scientific ideas identified for all four grade spans, K-2, 3-5, 6-8 and 9-12, to generate the performance expectations. The performance expectations describe what students are expected to know and how they should be able to use the scientific ideas described in Table 1. (Note that the scientific ideas in Table 1 also appear in the corresponding table in the prototype learning progression in Chapter 7).

The examples provided in Table 1 also include a brief description of the criteria that would be used to judge the quality and success of the performance. These are the relevant features that are applicable to each specific case. By choosing successive grade bands and related content, we show how the performance expectations and criteria for success would increase in sophistication across the extended time frame of 12+ years of instruction. Across such an instructional span, the content increases in depth of knowledge and sophistication as does the nature of the practices applied to the content leading to integrated performance expectations that reflect both deeper conceptual knowledge and more sophisticated reasoning.

For the case of the Physical Sciences (see Table 2), we have generated similar examples by choosing a Core Idea (PS1 – Structure and Properties of Matter), a Component Idea (PS1.A – The Structure of Matter) and selected key scientific ideas to produce performance expectations for the successive grade spans of K-2, 3-5, 6-8 and 9-12. The format of Table 2 matches that in Table 1 and it describes both the integrated performance at each grade band as well as the criteria for judging quality and success.

To summarize, each performance represents the combination of a scientific idea with a scientific practice. The scientific ideas are drawn from Dimension 1, specifically the prototype learning progressions described in Chapter 7. The practices are drawn from the description of Dimension 3 in Chapter 5. For each performance, the criteria on which to judge a student's performance are listed last.

Table 1: Sample Performance Expectations in the Life Sciences

LS1.C: Organization for Matter and Energy Flow in Organisms

Sub-question: *How do organisms get and use the matter and energy they need to live and grow?*

Organisms deploy a variety of chemical reactions to live and grow. These reactions require the input of energy. The energy needed is ultimately derived from the sun and transformed into chemical energy by plants and other energy-fixing organisms such as bacteria to maintain their activities and sustain the rest of the food chain. The complexity and organization of organisms accommodates the need for obtaining, transforming, transporting, releasing, and eliminating the matter and energy used to sustain the organisms.

Grades K – 2	Grades 3 – 5	Grades 6 – 8	Grades 9 - 12
Scientific Idea All living things grow, reproduce, and respond to their environment. Animals and plants meet their needs for survival in different ways. Plants and animals both need to take in water, and animals need to take in food. In addition, plants need light and minerals. ***Scientific Practice*** Supporting claims with evidence ***Performance*** Identify two things that all living things have in common and provide evidence.	***Scientific Idea*** From food, people and other animals obtain fuel (energy) and materials for body repair and growth. ***Scientific Practice*** Supporting claims with evidence ***Performance*** Identify two important ways that food is used by animals, and provide evidence of each type of use. ***Criteria*** A full description should include both building materials and use of	***Scientific Ideas*** In order to release the energy stored in food, oxygen must be supplied to cells and carbon dioxide removed. The way in which all cells function is similar in all living organisms. Within cells many of the basic functions of organisms, such as releasing energy from food and getting rid of waste are carried out. ***Scientific Practice*** Constructing explanations ***Performance*** Construct an explanation of why when a human breathes out, the air contains a lower proportion	***Scientific Idea*** As matter and energy flow through different levels of organization of living systems – cells, organs, organisms, communities – chemical elements are recombined in different ways to form different products. Energy is transferred when the bonds of food molecules are broken and new compounds with lower energy are formed. Some of the energy is used to change ADP, an inorganic phosphate (low energy), into ATP, an energy carrier that functions in a variety of pathways. ***Scientific Practice*** Modeling ***Performance***

Criteria Common characteristics should include growing, reproducing, or responding to the environment. Evidence should include specific examples of an organism exhibiting the characteristic, such as plants growing in height or increasing its number of leaves over several weeks, or turning toward the sun as responding to the environment.	energy, with an example of building materials consisting of growth or repair, and uses of energy consisting of internal work (heart beating) or external work (movement, breathing) by the body. The evidence for growth and repair should identify use of the food's mass in the process. Evidence for energy use should refer to the need for energy transfer in the performance of the activity.	of oxygen than the air he or she breathed in. The explanation should address where in the body the oxygen was used, and how it was used. ***Criteria*** A full explanation should contain a claim about oxygen being used in all the cells of the body as part of the chemical reaction that releases energy from food, and support the claim with reasoning about the role of oxygen in chemical reactions releasing energy, and how the oxygen and food substances are transported to the cells through the body systems.	Construct a model that explains the chemical processes that enable human cells to obtain and transfer energy to meet their needs. . ***Criteria*** The model should describe how the reaction of various compounds, including oxidation of sugars and conversion of ADP to ATP are involved in transferring energy in cells throughout the body.

Table 2: Sample Performance Expectations in the Physical Sciences

PS1.A: The Structure of Matter ***Sub-question:*** *What makes up everything around us?* All substances are made up of atoms that are in constant motion. These particles are too small to be seen even with a light microscope. Atoms have substructure that determines how they combine, arrange and interact to form all of the substances around us.			
Grades K – 2	Grades 3 - 5	Grades 6 – 8	Grades 9 – 12
Content: The same materials can exist in as a solid or a liquid depending on the temperature. Solids have a definite shape while liquids flow to the lowest level in the container. ***Practice:*** Supporting claims by providing evidence. ***Performance:*** Students support claims as to whether something is a solid or a liquid by providing descriptive evidence. ***Criteria:*** Descriptive evidence that a material is a solid would include that object has a definite shape and for a liquid that the material takes the shape of	***Content:*** All substances are considered matter. Matter can exist in different forms, or states. In all forms, it can be felt and weighed. It is possible to break materials apart into pieces too tiny to see with our eyes. However, the material still exists and continues to have weight even though we can't see it. ***Practice:*** *Design experiments to collect evidence* ***Performance:*** Students provide strategies for collecting evidence as to whether matter still exists even if it isn't visible.	***Content:*** Substances can exist in different states depending on temperature and pressure. Matter consists of extremely tiny particles that cannot be seen with a light microscope, are constantly in motion, with interactions between the particles, can explain states of matter and changes of matter with temperature ***Practice:*** *Modeling* ***Performance:*** Students create molecular level models to explain the differences between the solid, liquid and gaseous state of a substance. ***Criteria:*** The model should show the following: Particles	***Content:*** Atoms have substructure. The patterns of the periodic table can be related to the patterns of the outermost electrons in the atom, which are those that are involved in chemical bonding. Models of electrical attractions and repulsions involving electrons and atomic nuclei help explain the structure and many properties of substances. ***Practice:*** *Modeling* ***Performance:*** Students develop models that show why atoms of some elements react readily with the atoms of other elements. ***Criteria:*** The model should

the container or that the material flows to the lowest part of the container.	***Criteria:*** Design includes ways to measure weight with and without an invisible substance (gas or solute) present. For example, weighing a sealed container with different amounts of air, such as an inflated and deflated basketball, or weighing pure water and some salt/sugar before and after mixing them together.	in all solids 1) are close together;2) limited in motion, vibrate in place; 3) cannot move past or around each other; and thus are fixed in position relative to each other. The particles in a liquid 1) are about as close together as in a solid, 2) are always disordered, 3) have greater freedom to move than in a solid, and 4) can slide past one another and move with a range of speeds. Gas particles 1) are much further away from each other than in solid or liquid form, 2) are always disordered, and 3) move freely with a range of speeds and 4) sometimes collide with each other and bounce off	show the following: the atom consists of inner core called the nucleus, which consists of protons and neutrons, that the number of protons in the nucleus determines the element, and that the nucleus is much smaller in size than the atom. The outer part of the atom contains electrons. In a neutral atom, the number of electrons matches the number of protons because protons and electrons have opposite electric charge. The electrons occupy a set of "layered" states with a given number allowed in each of the first few layers. (2,8,8). (Details of orbitals and reasons behind counting of states not expected) The "outermost" position of the electrons correspond to the least bound electrons. The filling level of the "outermost" layer can be used to explain properties, including why some elements react with other elements, by "sharing" or "exchanging" their combined "outer" electrons to give filled levels.

Note that what we have illustrated in Tables 1 and 2 is just a beginning illustration of the performance expectations that might be expected at each grade band. For any given aspect of content knowledge, multiple practices could be matched to that content to yield additional appropriate performance expectations. Assessments should use a broad set across the multiple items. In addition, the criteria used to judge the quality of a given performance outcome need to include a specification of the features of the practice (a description, model, explanation, etc.), that are relevant for the specific content and grade band. As shown earlier in our presentation of Dimension 3 practices, the expectations regarding how these practices develop over grade bands reflect an increasing sophistication in the use of information and the assembly of descriptions, explanations and arguments. For examples of performance expectations that similarly link content and practice and that are appropriate for formulating both classroom-based and large-scale assessments of whether students have mastered particular standards, we refer the reader to the College Board "Science Standards for College Success" document, which contains many such examples in areas of the life sciences, physical sciences, and earth sciences (College Board, 2009).

Chapter 7

Prototype Learning Progressions

Research indicates that one of the best ways for students to learn the core concepts of science is to learn successively more sophisticated ways of thinking about these ideas over multiple years. These are known as "learning progressions." If mastery of a core idea in science is the ultimate educational destination, learning progressions are the routes that can be taken to reach that destination. Learning progressions can extend all the way from preschool to twelfth grade and beyond—indeed, people can continue learning about core ideas in science their whole lives. A well-designed learning progression will include the essential component ideas and principles necessary to understand a core idea in science. Because learning progressions extend over multiple years, they prompt educators to think about how topics are presented at each grade level so that they build on and support each other.

More specifically, learning progressions are anchored on one end by what is known about the concepts and reasoning of students entering school. There is now an extensive research base at this end (NRC, 2007), although much of it is not widely known or used by the science education community. At the other end, learning progressions are anchored by expectations (values) about what all students need to understand about science by the end of high school. They are also constrained by research-based conceptual and social analyses of the structure of the disciplinary knowledge and practices that are to be learned. Analysis of disciplinary knowledge is important in helping to identify the core ideas in science. It also helps identify the network of ideas and practices on which those core ideas rest, and hence what will be important component ideas to develop as part of their construction.

Between these anchor points, learning progressions propose the intermediate understandings that are reasonably coherent networks of ideas and practices and that contribute to building a more mature understanding. It is important to note that some of the important precursor ideas may not look like the later ideas. For example, research has found that recognition that objects are composed of specific materials and have certain properties because of those materials is an important first step toward eventual understanding of atomic-molecular theory. Carefully developed learning progressions that consider how students' initial understandings could be built on to develop more sophisticated understandings can highlight important precursor understandings that might otherwise be overlooked by teachers and educators. In the progressions in the framework we refer to these precursor ideas as "building block" ideas.

ARTICULATING THE PROGRESSIONS

In this chapter we provide prototype learning progressions for each component of the core ideas described in the chapter on Dimension 1: Disciplinary Core Ideas (Chapter 3). We present the progressions in two ways: as detailed tables and, for some select examples, as more elaborated narratives. In this interim draft only the tables are fully developed. We provide one narrative as an example of what we intend to include in the final report.

The tables are organized first by discipline, then by core idea within that discipline, and finally by component idea (see Chapter 3 for a reminder of the core ideas and component ideas for each discipline). The tables represent the committee's best judgment about the appropriate learning progression for a given component idea. Where research on how children develop understanding of this topic exists, the progression reflects that research, but in many cases there is not sufficient research and we propose hypothetical progressions based on the examples that have been studied. For this reason we refer to the progressions as "prototype" learning progressions to distinguish them from learning progressions being developed by researchers. The latter include significant attention to instruction and assessment as well as to students' developing understanding, and are more fully grounded in research on learning and teaching. The committee also drew on the conceptual strand maps in the *Atlas of Science Literacy (AAAS)* to inform the prototype progressions.

All of the tables follow one general trend across grades. In K-2, we choose ideas about phenomena that students can directly experience and investigate. In 3-5, we include invisible but still macroscopic entities, such as what is inside the body or the earth, for which children will have little direct experience. However, physical models and pictures can represent them in a way that children can investigate and interpret. At the 6-8 level we move to atomic level explanations of physical phenomena and cellular level explanations of life processes and structures, but without detail of the inner workings of an atom or a cell. Finally, at the 9-12 level, we move to sub-atomic and sub-cellular explanations. In this way, the progression articulates increasingly complex types of explanatory models building from the earlier to the high school grades, starting from simple cause and effect models in K-2 to develop more complex multi-step and multi-factor models in 6-8, with more abstract tracking of causality in 9-12, including consideration of very short or very long time scales, and treatment of emergent phenomena in non-linear systems. This progression is common across all the content strands.

Sample Narrative Description

While the tables that follow outline a progression of building block ideas for each component of each core idea, we also include here a narrative description that illustrates how one component idea can be developed over the K-12 years. The narrative provides rich descriptions of the kinds of learning experiences for students that can support a deepening understanding of the component idea. The example is based on a component idea – properties of materials depend on their sub-atomic structures -- where the sequence of experiences to support student learning has been studied in some detail. The purpose of this example is to stress that in order for students to move successfully through the learning progressions, they need a carefully designed progression of instructional experiences.

The narrative example also illustrates how much work will be required to go from this framework to fully developed curricula for the classroom. The prototype learning progressions we provide in the detailed tables do not include descriptions of the types of learning experiences that are critical for supporting each step in a student's conceptual development. Additional research and development work is needed in order to determine what kinds of instructional supports are needed and places where the progressions may need to be modified.

PS1.A: The Structure of Matter

Sub-question: *What makes up everything around us?*

All substances are made up of atoms that are in constant motion. These particles are too small to be seen even with a light microscope. Atoms themselves have substructure that determines how they combine, arrange and interact to form all of the substances around us.

Description of the Component Idea Develops Across Grade Bands

Motivating Questions and Contexts	**Ideas**
Grades K-2	
What kind of parts are objects made of? (Macroscopic) Sub-questions: • What happens when I take objects apart? • Do the parts of objects behave like the object? At this level, students begin to explore the parts and materials that make up the things around them and how they are put together.	At the earliest level, students need experiences with a range of macroscopic objects to realize that objects can be built up from parts and to observe that objects are often made up of different materials. Through experiences with multiple objects and materials, young learners should be able to explain in what ways the identity, characteristics and function of an object depends on the materials/building blocks used to make it, and the way they fit together. These observations and experiences also lead students to describe a great variety of materials, some natural, others manufactured. Direct experiences show students that some materials can exist in as a solid or a liquid depending on temperature of the material. Through experiences they make a generalization that solids have a definite shape while liquids flow to the lowest level of the container. (Note: at this age we do not engage students with gases).
Grades 3 - 5	
How do the parts of an object affect its structure and function? (Macroscopic) Sub-questions: • Do the pieces of materials behave the same why as the object? • What happens when I heat materials? At this level, students learn to characterize the world around them by have multiple experiences with objects and materials in the real world.	At this level, students continue to need experiences with a range of materials to develop their understanding to a deeper level of complexity. Here experiences are chosen so that students can recognize and explain that a great variety of objects can be made with just a few types of components. By taking objects apart and building objects, they can explain how the structure, properties and uses of the objects depend on the nature of the components and they ways they attach to one-another, and that the objects can be quite different from those of the components. They can also use their understanding about the characteristics of materials to help design uses of them. Moreover, directed experiences allow students to realize that it possible to break materials apart into pieces too tiny to see with our eyes. However, the material still exists and continues to have weight even though we can't see it. Further

	explorations with materials and their properties allow students to transition to conceptions of substance and forms of matter. They recognize that matter that can exist in different forms, or states: solid, liquid and gas and are able to identify the different states of materials. They are aware that, in all forms, matter can be felt and weighed. They can describe and provide examples that show solids have definite shape and volume, whereas liquids also occupy definite volume, but not shape, and gases are made of particles too small to see that move around throughout the full volume of any container. Their experiences give them the background to provide evidence for the existence of gases.
Grades 6-8	
How do the building blocks of matter help explain the diversity of materials that exist in the world? <u>Sub-questions</u>: • What are materials and substances made of and what determines their properties? • How can so many materials exist in the world? • How can matter change states? • How do old substances make new substances? • What changes and what stays the same when things interact and transform (e.g., smells diffusing across the room; substances during phase changes)? These questions require students to develop a basic particle model of matter to explain phenomena such as phase changes, diffusion and chemical reactions.	At this level, students develop an understanding of the particle model of matter to explain phenomena around them. Through directed experiences with matter and with simulations, students first develop a basic particle model that does not distinguish whether particles are atoms or molecules but includes the ideas that matter consists of extremely tiny particles that cannot be seen with a light microscope, are constantly in motion, with interactions between the particles. At this level, there is no need for a model of the particles that is more complex than a sphere with no components when explaining phenomena. Students can use this particulate model to describe and explain the different states of substances that exist depending on temperature and pressure. They can present and differentiate appropriate models for the particulate organization of matter in the solid, liquid and gaseous states. These models include features such as: the particles in all solids are close together; the motion of the particles in a solid is limited; they cannot move past or around each other so they are fixed in position relative to each other. The particles in a liquid are about as close together as in a solid; the particles are always disordered; particles in liquids have greater freedom to move because the particles that make up a liquid can slide past one another and move with a range of speeds; gas particles are much further away from each other than in solid or liquid form; they are always disordered; gas particles can move freely around and past each other with a range of speeds. Students can provide evidence that shows that, regardless of the state, all matter has mass, and the mass does not change when matter goes from one state to another. With more experiences with various substances and their

	transformations, students develop an understanding that the particles in these descriptions are atoms or molecules and that the immense variation and number of substances, all are made from a limited number of types of atoms, called elements. Each type of atom had distinct mass and chemical properties. Students also can use the particle model to explain changes in matter as a result of atoms interacting by arranging and combining in various ways to form well-defined molecules or arrange in extended patterns with no defined endpoint. Through experiences with chemical transformations and simulations, their conceptual understanding develops to include the idea that the number and types of atoms always remain the same when atoms rearrange to form new substances. Students see a pattern or material changes in chemical processes that leads them to the idea that the diversity of materials and substances that exist in the world result from a limited number of atoms. With both first and second hand experiences of elements, particularly the first 20 elements, students begin to see a pattern of uniformity in the mass and chemical properties of each element. They recognize that the Periodic Table organizes the elements by their mass and chemical properties and provides a useful reference for predicting how they will combine. A key idea of the particle model that students develop is that thermal motion of the atoms increases with temperature. Using their more developed understanding, students can explain that the chemical composition, the arrangement of atoms, and the way they interact and move determines the state and properties of a substance.
Grades 9-12	
In what ways do the building blocks (atoms) combine to create all of the substances and structures in the universe? Sub-questions: • What is different about each element that makes it react the way it does? • Why is it that the atoms of certain elements combine and	More advanced experiences with phenomena, give rise to questions of about why particular elements interact with particular other elements and why substances have different properties. These experiences create a need for a more sophisticated view of the atom and its structure. Students develop understanding that the atom consists of inner core called the nucleus, which consists of protons and neutrons, that the number of protons in the nucleus determines the element, and that the nucleus is much smaller in size than the atom but contains most of the mass of the atom. The outer part of the atom contains electrons. In a neutral atom, the

others do not? • Why do atoms combine in only certain ways? These questions create a need for a more sophisticated model for the structure and behavior of matter and a more sophisticated model of atomic structure will provide explanations for the more complex phenomena that students observe.	number of electrons matches the number of protons because protons and electrons have opposite electric charge. However, the mass of the electron is negligible compared to that of a proton and neutron. Moreover, the outer most electrons in substances can be used to explain properties. Using this understanding of the structure of atoms and through both first and second-hand experiences with different elements and their reactions, students see how patterns in the periodic table can be related to the patterns of the outermost electrons in the atom, which are those that are involved in chemical bonding. The model of electron distributions in atoms used at this level is a generalized and simplified description, and no attempt to fully describe or explain it is made, except to say that it is quantum in nature, so that electrons occupy definite energy states, and the "outermost" states correspond to the least bound electrons. Student understandings about the structure of atoms and electrical forces are used to explain how atoms interact with each other to form new substances. Students can explain that there is a hierarchy of structure within matter. Atoms may interact to form individual molecules, network or lattices with no defined endpoint through a range of electrical forces. Atoms and molecules combine to form larger, more complex structures, natural or manufactured, with an extensive range of properties. (*link to ET1.x)*. Moreover, the structures made of atoms and molecules exist over a huge range of scales—from diatomic molecules in a gas to stars. Students can use their more developed understanding to explain the diversity of molecules and structures that exist in the physical and biological world Using their more advanced understanding of the structure of atoms, students develop deeper conceptual understanding of the forms of matter to extend to plasma and that states of substances depend on pressure as well as temperature. They recognize that the variety of substances and their rates of change can challenge everyday classification (e.g., glasses, gels, colloids).

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Life Science (LS) Core Idea 1: Organisms have structures and functions that facilitate their life processes, growth, and reproduction. [Molecules to Organisms: Structures and Processes]

LS1.A: Structure and Function

Sub-question*: How do the structures of organisms help them to perform life's functions?*

Organisms have characteristic structures (anatomy and morphology) and functions (physiology) to support life processes. Organisms and their parts are made of cells, which are the structural and functional units of life.

Grades K – 2

How do living things meet their basic needs?

All living things have various external parts. Different animals use their body parts in different ways to see, hear, grasp objects, seek, find and take in food and move from place to place. Plants also have different parts that help them meet their needs.

Grades 3 – 5

How do organisms use their structures to grow, survive and reproduce?

The internal and external structures of plants and animals serve various functions in growth, survival, and reproduction.

Grades 6 – 8

How do cells within organisms help them perform the essential functions of life?

All living things are made up of cells. Organisms may consist of one single cell or many different numbers and types of cells.

Special structures within cells are responsible for various functions (e.g., mitochondria in plants and animals extract energy from food, and chloroplasts in plants use light to make food). The cell membrane forms the boundary that controls what enters and leaves the cell. These include the molecules needed to carry out life functions.

Micro-organisms consist of a single cell. Like multicellular organisms, microorganisms need food, water, and air, a way to dispose of waste, and an environment they can live in.

Grades 9 – 12

How do systems of specialized cells within organisms help them perform the essential functions of life?

The essential functions of a cell involve chemical reactions that take place between many different types of molecules, including water, carbohydrates, lipids, nucleic acids and proteins, and are facilitated by enzymes.

Proteins carry out the work of cells. They form important structural components of the cell and provide energy. Enzymes, which are proteins, are responsible for facilitating life processes. The breakdown of complex molecules, the release and capture of energy in new chemical forms, and the synthesis of new biomolecules are all carried out by proteins.

Proteins function as hormones and neurotransmitters. They serve as signaling devices and are involved in regulating the activities of the cells.

Many factors influence an enzyme's activity and its ability to regulate chemical reactions for life's functions.

The types and concentrations of molecules within cells are regulated. The cell membrane controls what enters and leaves the cell.

Feedback communication maintains a living system's internal conditions within certain limits (e.g., temperature, molecular concentration, pH), allowing it to remain alive and functional even as external conditions are changing. Feedback mechanisms can encourage (positive feedback) or discourage (negative feedback) what is going on.

Life Science (LS) Core Idea 1: Organisms have structures and functions that facilitate their life processes, growth, and reproduction. [Molecules to Organisms: Structures and Processes]

LS1.B: **Growth and Development of Organisms**

Sub-question: *How do the structure and functioning of organisms change as they grow and develop?*

The characteristic structures (anatomy) and functions (physiology) of organisms change in predictable ways as they develop, from birth to old age.

Grades K – 2

How do plants and animals grow?

All animals have offspring, usually with two parents involved.

Living things have predictable characteristics at different stages of development.

Grades 3 – 5

How do different organisms develop?

Reproduction is essential to the continuation of every kind of organism.

Plants and animals have life cycles that include being born (sprouting in plants), developing into adults, reproducing, and eventually dying. The details of the life cycle vary for different organisms.

Grades 6 – 8

How do different organisms continue their type (species)?

All organisms reproduce and transfer their genetic information to their offspring.

Grades 9 – 12

How is genetic information transmitted between parent and offspring after fertilization?

A fertilized egg divides by mitosis into many cells. As successive generations of an embryo's cells form, small differences in their immediate environments cause them to develop slightly differently, by activating or inactivating different parts of the DNA information, thus producing cells which are different. As they divide, they produce cells with different functions.

The many body cells in an individual can be very different from one another, even though they are all descended from a single cell and thus have essentially identical genetic instructions. Different parts of the instructions are used in different types of cells, influenced by the cell's environment and past history.

Life Science (LS) Core Idea 1: Organisms have structures and functions that facilitate their life processes, growth, and reproduction. [Molecules to Organisms: Structures and Processes]

LS1.C: Organization for Matter and Energy Flow in Organisms

***Sub-question**: How do organisms get and use the matter and energy they need to live and grow?*

Organisms deploy a variety of chemical reactions to live and grow. These reactions require the input of energy. The energy needed is ultimately derived from the sun and transformed into chemical energy by plants and other energy-fixing organisms such as bacteria to maintain their activities and sustain the rest of the food chain. The complexity and organization of organisms accommodates the need for obtaining, transforming, transporting, releasing, and eliminating the matter and energy used to sustain the organisms.

Grades K – 2

How do living things get and use what they need to live and grow?
All living things grow, reproduce, and respond to their environment. Animals and plants meet their needs for survival in different ways. Plants and animals both need to take in water, and animals need to take in food. In addition, plants need light and minerals.

Grades 3 – 5

How do organisms get the matter and energy they need from what they get from the environment?
People and other animals take in the oxygen they need to live by breathing.

The digestive system breaks down the food we eat into a form that can be used by the body.

From food, people and other animals obtain fuel (energy) and materials for body repair and growth.

Grades 6 – 8

What happens inside organisms to enable them to get and use the energy and materials from food?
For the body to use food for energy and building materials, the food must first be digested into molecules that are absorbed and transported to cells.

In order to release the energy stored in food, oxygen must be supplied to cells and carbon dioxide removed.

Lungs take in oxygen for the combustion of food, and they eliminate the carbon dioxide produced.

The circulatory system moves all these substances to or from cells where they are needed or produced.

The way in which all cells function is similar in all living organisms. Within cells many of the basic functions of organisms, such as releasing energy from food and getting rid of waste, are carried out by different cell elements.

In plants and animals, molecules from food react with oxygen to provide energy that is needed to carry out life functions, build and become incorporated into the body structure, or is stored for later use.

Matter moves within individual organisms through a series of chemical reactions in which food is broken down and rearranged to form new molecules.

Plants use the energy from light to make sugars (food) from carbon dioxide and water. This process transforms light energy from the sun into stored chemical energy.

Minerals and other nutrients from the soil are not food (they don't provide energy), but they are needed for plants to make complex molecules from the sugar they make.

Grades 9 – 12

What chemical processes occur in organisms to transfer and transform matter and energy so they can live and grow?
As matter and energy flow through different levels of organization of living systems – cells, organs, organisms, communities – chemical elements are recombined in different ways to form different products.

During these chemical reactions energy is transferred from one system of interacting molecules to another. Some of the energy in these reactions is transferred to the environment as thermal energy (heat).

Matter and energy are conserved in each change.

Through photosynthesis, plants take energy from light to form sugar molecules (high energy level) containing carbon, hydrogen, and oxygen from lower energy molecules. These sugar molecules can be used to make amino acids and other carbon-containing molecules and assembled into larger molecules with biological activity.

Energy is transferred when the bonds of food molecules are broken and new compounds with lower energy are formed. Some of the energy is used to change ADP, an inorganic phosphate (low energy), into ATP, an energy carrier that functions in a variety of pathways.

LS Core Idea 2: Organisms have mechanisms and processes for passing traits and variations of traits from one generation to the next. [Heredity: Inheritance and Variation of Traits]

LS2.A: Inheritance of Traits

Sub-question: *How are the characteristics of one generation of organisms related to the next generation?*

When organisms reproduce, they transfer their genetic information to the next generation.

Grades K – 2

How are parents and offspring alike?

Living things possess characteristics that can be recognized and described as either similar or different (e.g. number of legs, eye color, fur type, gender)

Offspring are very much, but not exactly, like their parents and like one another.

Grades 3 – 5

Why do offspring resemble their parents?

Many characteristics of organisms are inherited from the parents. Other characteristics result from an individual's interaction with the environment. Many characteristics involve both inheritance and the individual's interaction with the environment.

Each parent contributes information that results in characteristics (i.e., traits) in the offspring.

Grades 6 – 8

How are the inherited characteristics distributed to offspring?

Humans and other animals, plants, fungi, and bacteria have genes (i.e., genetic information) in the chromosomes of the cells.

Transmission of genetic information to offspring occurs through egg and sperm cells that contain only one representative from each chromosome pair. An egg and a sperm unite to form a new individual. The fact that the human body is formed from cells that contain two copies of each chromosome—and therefore two copies of each gene—explains many features of human heredity, such as how variations that are hidden in one generation can be expressed in the next.

Cells divide to make new cells each with all the genetic information.

Genes are instructions for molecules (many of which are proteins) that carry out functions within the organism. All organisms use the same genetic language for their instructions.

The proteins that are made as a result of genetic instructions result in observable traits (e.g., skin color results from amount of a pigment-melanin). Different kinds of genes make different proteins that produce different traits.

Changes (mutations) to genes can result in changes to proteins, which can affect the structures and functions in the organism (and thereby change traits).

Grades 9 – 12

How is the genetic information stored within the molecules of a cell?

In all organisms, the instructions for specifying its characteristics are carried in DNA, a large polymer formed from subunits of four kinds (A, G, C, and T). The chemical and structural properties of DNA encode the genetic information that underlies heredity replicated by cellular mechanisms.

Almost all organisms use the same genetic code.

One of the triumphs of modern biology is the demonstration that DNA is the genetic material, and that DNA is *transcribed* into a "messenger" RNA, which is in turn *translated* by the cellular machinery into a protein. Thus, a gene is a segment of DNA with a specific nucleotide sequence that specifies the sequence of amino acids in a protein. In turn, proteins determine an organism's identifiable traits.

Proteins have particular three-dimensional shape determined by their amino acid sequence. Proteins have many different kinds of functions that depend on their specific properties. There are different types of genetic mutations that can affect the structure and thus function of proteins and ultimately the traits.

All cells in an organism have the same genetic content, but the genes used by the cell (expressed) may be regulated in different ways.

LS Core Idea 2: Organisms have mechanisms and processes for passing traits and variations of traits from one generation to the next. [Heredity: Inheritance and Variation of Traits]

LS2.B: Variation of Traits

Sub-question: *Why do individuals of the same species vary in how they look and function?*

Variations arise from genetic differences inherited as a result of mutations and sexual reproduction, and of environmental factors.

Grades K – 2

Are all individuals of one kind the same?

Offspring are very much, but not exactly, like their parents.

Grades 3 – 5

How do offspring vary from their parents?

Offspring have a mix of characteristics from their parents.

Different organisms vary in how they look and function because they have different inherited information. Even within one kind of organism there is variation in traits.

Organisms vary in how they grow and function. For any given trait there are variations. Different organisms may have different versions of the trait.

Organisms that are related may end up looking or behaving differently.

Grades 6 – 8

How do variations occur as inherited characteristics are passed to offspring?

Cells divide to make new cells each with all the genetic information. Before cells divide, the chromosome sets are duplicated and then two new cells are formed, each with two chromosomal sets identical to those of the parent cell.

In sexually reproducing organisms each parent contributes half the genes (genetic information) to the new generation.

The cells (except sex cells) in a human contain two copies of each of 22 different chromosomes. In addition, there is a pair of chromosomes that determines sex: a female contains two X chromosomes and a male contains one X and one Y chromosome.

In sexually reproducing organisms, chromosome sets are randomly assorted into gametes through the process of meiosis (one full set into each sex cell). This process creates sex cells that have only one set of chromosomes.

Different versions of the same gene on a chromosome are called alleles. Each chromosome has one allele of each gene that it carries. Individuals have two alleles of each gene, one from each parent. These versions may be identical or differ from one another.

An observed trait depends upon the set of alleles the offspring inherits from each parent, as well as the specific relationship between the alleles (e.g., dominant, recessive, codominant, etc.). Therefore, siblings (except for identical twins) will have different combinations of traits.

In addition to variations that arise from sexual reproduction, genetic information can sometimes change due to mutations. Mutations in the genetic information are rare but can result in changes to the structure and function of proteins. Some changes can be beneficial, others harmful, and some neutral to the organism in its environment.

Genes operate in a broader environmental context. Cells can respond to environmental changes by altering specific constituents.

LS Core Idea 2: Organisms have mechanisms and processes for passing traits and variations of traits from one generation to the next. [Heredity: Inheritance and Variation of Traits]

Grades 6 – 8

Grades 9 – 12

How do variations occur in the genetic information stored within the molecules of a cell?

The information passed from parents to offspring is coded in the DNA molecules. Genes are made of nucleotide sequences within the DNA molecule. DNA molecules make up the chromosomes that together form each individual's genome.

DNA replication is tightly regulated to prevent errors. But errors do occur.

Usually genes on the same chromosome are inherited together. However, occasionally during the process of meiosis chromosomes can swap sections (crossing over) and create new genetic combinations. This creates more genetic variation.

Gene variants – alleles – differ in their nucleotide sequence, resulting in different or even missing proteins that affect an individual's phenotype. Dominant and recessive genetic relationships can be explained at the molecular level as a consequence of the function and interaction of gene products.

DNA mutations are the source of new genetic variation.

Some DNA sequences can vary between species while others do not; therefore, we share some genes with other species.

Environmental factors can cause mutations in genes, or alter gene expression.

LS Core Idea 3:Organisms and populations of organisms obtain necessary resources from their environment which includes other organisms and physical factors. [Ecosystems: Interactions, Energy, and Dynamics]

LS3.A: Interdependent Relationships in Ecosystems

Sub-question*: How do organisms depend on the feeding relationships of one another and of the physical (abiotic) environment?*

Organisms interact with one another in complex feeding relationships. These relationships result from the fact that organisms must obtain the necessary resources for life from their environment which consists of biotic and abiotic factors.

Grades K – 2

Where do animals get food?

Animals depend on plants and other animals for food. When animals and plants (or plant parts) die, they are fed upon by tiny organisms that break them apart.

Plants depend on air, water and light to grow.

Grades 3 – 5

How do different organisms depend on their environment for food?

The food of almost all kinds of animals can be traced back to plants. Some animals eat plants for food. Other animals eat animals that eat plants.

Some organisms such as fungi and bacteria operate as decomposers. Decomposition eventually restores (recycles) some materials back to the soil for plants to use, and to repeat the food chain cycle.

Organisms can survive only in environments in which their needs are met.

Grades 6 – 8

How do different organisms interact and depend on their ecosystem?

Organisms and populations of organisms are dependent on their interactions with other living things (biotic) and their interactions with non-living (abiotic) factors in the environment, which together make up its ecosystem.

In any environment, organisms and populations with similar requirements for food, water, air, or other resources may compete with each other for limited resources. The growth and reproduction of an organism and of populations will be constrained by access to these limited resources.

Organisms and populations in any environment interact in characteristic ways. Although the particular species of organisms vary in different ecosystems, the same types of interactions are found.

The interactions between organisms in a given environment may be competitive or mutually beneficial. Competitive interactions may reduce the number of organisms or eliminate populations of organisms. Mutually beneficial interactions may become so interdependent that each requires the other for survival.

Grades 9 – 12

What limits the interaction of organisms in ecosystems?

Ecosystems have carrying capacities, which are limits to the numbers and types of organisms and populations an ecosystem can support. These limits are a result of such factors as availability of biotic and abiotic resources, and biotic challenges such as predation, competition, and disease.

Organisms have the capacity to produce populations of great size, but environments and resources are finite. This fundamental tension has effects on the interactions between organisms.

LS Core Idea 3:Organisms and populations of organisms obtain necessary resources from their environment which includes other organisms and physical factors. [Ecosystems: Interactions, Energy, and Dynamics]

LS3.B: Flow of Matter and Energy Transfer in Ecosystems

Sub-question: *How do organisms in an ecosystem get the materials and energy they need?*

Organisms obtain the necessary resources for life from their environment which consists of biotic and abiotic factors. Materials cycle within ecosystems through interaction with different organisms.

Grades K – 2

Where do organisms get what they need to live?

Living things get the materials they need to grow and survive from the environment.

Many materials from living things are used again by other living things.

Grades 3 – 5

Where do organisms get the matter and energy they need?

Some source of energy is needed for all organisms to stay alive and grow.

From food, people and other animals obtain fuel (i.e., energy) and materials for body repair, growth, and reproduction.

Organisms are related in food webs, with plants, animals that eat those plants, and animals that eat those animals.

Some organisms (i.e., bacteria and fungi) break down waste and dead organisms, and return materials to the soil.

Grades 6 – 8

What happens to the matter and energy when organisms use food?

In plants and animals, molecules from food a) react with oxygen to provide energy that is needed to carry out life functions, b) build and become incorporated into the body structure, or c) are stored for later use. (Also in Matter and Energy)

Chemical energy is transferred from one organism in an ecosystem to another as the organisms interact with each other for food.

Matter is transferred among organisms in an ecosystem when organisms eat, or are eaten by others for food.

Matter is transferred from organisms to the physical environment when molecules from food react with oxygen to produce carbon dioxide and water in a process called cellular respiration.

The atoms that make up the organisms in an ecosystem are cycled repeatedly between the living and nonliving parts of the ecosystem.

Grades 9 – 12

How do matter and energy flow through an ecosystem?

All living systems require an input of energy to drive the chemical reactions in life functions and to compensate for the inefficient transfer of energy.

The chemical reactions in living systems involve the transfer of thermal energy (heat) to the environment. The thermal energy is no longer available to drive chemical reactions; therefore, a continuous source of energy is needed – the Sun.

In many organisms, the energy that keeps the chemical reactions in organisms going comes from the food that reacts with oxygen. The energy stored in that food ultimately comes from the Sun.

Some organisms utilize the energy transferred from the Sun to convert carbon dioxide and water into molecules in which carbon atoms are linked together and oxygen is released.

The chemical elements that make up the molecules of organisms pass through food webs and are combined and recombined in different ways. At each link in an ecosystem, some energy is stored in newly made structures.

As matter cycles and energy flows through different levels of organization of living systems, and between living systems and the physical environment, matter and energy are conserved in each change.

LS Core Idea 3:Organisms and populations of organisms obtain necessary resources from their environment which includes other organisms and physical factors. [Ecosystems: Interactions, Energy, and Dynamics]

LS3.C: Ecosystems Dynamics, Stability, and Resilience

Sub-question: *What happens to organisms and ecosystems when there are changes in the environment?*

Ecosystems dynamics can result in changes in the number and types of organisms and the survival, migration, and extinction of species.

Grades K – 2

How do environments change?
Environments continuously change and change can occur slowly or rapidly.

Grades 3 – 5

What happens to plants and animals when environments change?
When the environment changes, some plants and animals survive and reproduce; others move to new locations, and some die.

Grades 6 – 8

What happens when components of ecosystems change?
Ecosystems are *dynamic* in nature; the number and types of organisms and populations of organisms in ecosystems have continuous fluctuations over time.

Disruptions to the physical (abiotic) or biological (biotic) components of an ecosystem impact other components of an ecosystem.

Biodiversity, the variety of species, is used as a measure of the health of an ecosystem.

Grades 9 – 12

How do ecosystems change?
A complex set of interactions within an ecosystem can maintain the numbers and types of organisms in an ecosystem that is relatively constant over long periods of time.

The number of organisms in ecosystems fluctuates over time. Extreme fluctuations in size of populations challenge the stability of ecosystems in terms of resources and habitat availability.

If a biotic or abiotic disturbance to an ecosystem occurs, the affected system may return to being similar to the original system (that is, the ecosystem is resilient), or become a very different ecosystem.

Anthropogenic changes in the environment such as changes in climate, migration by an invasive species, and over-exploitation can impact the stability of an ecosystem.

LS Core Idea 4: Biological evolution explains the unity and diversity of species. [Biological Evolution: Unity and Diversity]

LS4.A: Evidence of Common Ancestry and Diversity

Sub-question: *How have organisms changed over time?*

The fossil record provides evidence of different life forms at different periods of geological history. The evidence supports the idea that newer life forms descended from older life forms. DNA provides further evidence for lines of descent from ancestral species to later-appearing species.

Grades K – 2

How do we know plants and animals lived a long time ago?
Fossils provide evidence about plants and animals that lived long ago.

Some kinds of plants and animals that once lived on Earth have completely disappeared, although they were something like other plants and animals that are alive today.

Grades 3 – 5

What can fossils tell us about the past?
Scientists have identified many plants, animals, and fungi. There are also many kinds of living organisms that can only be seen with a microscope.

Fossils provide evidence about the types of living organisms, both visible and microscopic, that lived long ago and the nature of the environments in which they lived.

Fossils can be compared to one another and to living organisms according to their similarities and differences.

Grades 6 – 8

What does the fossil record tell us about the history of life on Earth?
Thousands of layers of sedimentary rock provide evidence for the history of the Earth and changes in plants and animals whose fossil remains are found in the rocks. Recently deposited sedimentary rock layers are most likely to contain fossils resembling existing species of plants and animals.

Fossils are preserved remains or traces of organisms that provide evidence of past life. The collection of all fossils and their placement in chronological order (e.g., dating or location in sedimentary layers) is known as the fossil record. Because of the unique geological conditions that are required for preservation, not all organisms left fossils that can be retrieved.

The fossil record documents the existence, diversity, extinction and change over time of many life forms throughout Earth's history.

The existence of different life forms in different time periods led to the idea that newer life forms descended from older life forms.

Grades 9 – 12

How does genetic information provide evidence for evolution?
Anatomical similarities and differences among various organisms living today are compared to those of organisms in the fossil record in order to reconstruct evolutionary history and infer lines of evolutionary descent.

Organisms resemble their ancestors because genetic information (DNA) is transferred from ancestor to offspring during reproduction.

The branching that characterizes lines of descent can be inferred from the DNA composition of organisms over time.

The similarities and differences in DNA sequences, amino acid sequences, anatomical evidence, and fossil evidence provide information about the branching sequence of lines of evolutionary descent.

LS Core Idea 4: Biological evolution explains the unity and diversity of species. [Biological Evolution: Unity and Diversity]

LS4.B: Genetic Variation within a Species

Sub-question: *How does variation in organisms affect survival and reproduction?*

Genetic variation of individuals within a species gives some individuals an advantage to survive and reproduce.

Grades K – 2

Are there differences among individuals of the same kind?

There is variation among living things of one kind within a population.

Grades 3 – 5

How do differences between individuals matter?

Individuals of the same kind differ in their characteristics, and sometimes the differences give individuals an advantage in surviving and reproducing.

Grades 6 – 8

How can differences influence which organisms survive and reproduce?

Changes in environmental conditions can affect the survival of individual organisms and entire species.

Individuals with certain traits are more likely than others to survive and have offspring.

Grades 9 – 12

How does variation of organisms help them survive and reproduce as environments change?

Natural selection can occur only if there is variation in the genetic information between organisms of the same species in a population and variation in the expression of that genetic information as a trait. Genetic variation within a population influences the likelihood that a population will survive and produce offspring.

Sexual reproduction not only allows the continuation of traits in a population but also provides a source of genetic variation among the individuals of a population through genetic recombination. The expression of new anatomical, physiological and behavioral traits in organisms within a population can result from recombining existing genes. It also can occur by random sorting during sex cell production and fertilization. Variation within a population of organisms can also result from genetic mutations that create variation in the expression of traits between organisms of the same species.

In artificial selection, humans have the capacity to influence certain characteristics of organisms by choosing parents' desired characteristics, determined by genes, which in turn are passed on to their offspring.

LS Core Idea 4: Biological evolution explains the unity and diversity of species. [Biological Evolution: Unity and Diversity]

LS4.C: Natural Selection and Adaptation

Sub-question: *How does the environment influence populations of organisms?*

When an environment changes, there is a subsequent change in the supply of resources or biotic challenges. This results in selective pressures that influence the survival and reproduction of organisms and which lead to adaptations within populations.

Grades K – 2

What can influence the survival of living things?

Living things can survive only in environments in which their needs are met.

The world has many environments and distinct environments support different types of living things.

Grades 3 – 5

What happens to organisms when their environment changes?

Changes in an organism's habitat are sometimes beneficial to it and sometimes harmful.

For any particular environment, some kinds of plants and animals survive well, some survive less well, and some cannot survive at all.

Grades 6 – 8

How does variation of traits influence how populations of organisms can change?

Natural selection arises from three well-established observations: (1) There is genetically-based variation in traits within every species of organism, (2) some of these traits give some individuals advantage over others in survival and reproduction, and (3) those individuals that survive to adulthood will be more likely to have offspring which will themselves be more likely than others to survive and reproduce. When an environment changes, the advantage or disadvantage of characteristics can change.

Grades 9 – 12

How can different environmental factors lead to changes in populations of organisms?

Natural selection leads to a diversity of organisms that are anatomically, behaviorally and physiologically well suited to survive and reproduce in a specific environment.

Over time, the differential survival and reproduction of organisms within a population that have an advantageous heritable trait lead to an increase in the proportion of individuals in future generations that have the trait and a decrease in the proportion of individuals that do not.

Changes in the abiotic environment, including climatic and geological processes, have contributed to the decline of some species and the expansion of other species.

When environmental change—naturally occurring or human induced—happens, extinction can occur. Species become extinct because they cannot survive and reproduce in their environments. If members cannot adjust—because change in the environment is too fast or too drastic—they die or become unable to reproduce, thus closing off the opportunity for evolution.

Charles Darwin's theory of evolution had a dramatic effect on biology because of his use of clear and understandable argument and the inclusion of a massive array of evidence to support the argument. Later evidence continues to support and refine this theory.

LS Core Idea 4: Biological evolution explains the unity and diversity of species. [Biological Evolution: Unity and Diversity]

LS4.D: Biodiversity and Humans

Sub-question: *What is biodiversity and how do humans affect it and how does it affect humans?*

The diversity of genes, species, and ecosystems provide humans with renewable resources such as food, energy, and medicines. The resources of biological communities should be used within sustainable limits, but in many cases the human impact on them is exceeding sustainable limits.

Grades K – 2

Where do different kinds of living things live?

There are many different kinds of plants, animals and microbes in a region.

Different kinds of plants and animals live in different places and need different things to live.

Sometimes there are changes in the places where plants and animals live.

Grades 3 – 5

What happens when there are changes in the ecological conditions of places where organisms or groups of organisms live?

Scientists have identified many plants, animals, and fungi. There are also many kinds of living things that can only be seen with a microscope.

Organisms and populations of organisms live in a variety of habitats.

Humans, like all other organisms, get living and non-living things (e.g., resources) from their environments.

Change in habitats can be good, bad, or neither good nor bad (i.e., neutral) for a species.

Some plants and animals no longer exist on Earth (e.g., dinosaurs).

Grades 6 – 8

What happens when the diversity of life changes?

Biodiversity consists of different life forms (species) that have adapted to the variety of conditions on Earth. Biodiversity includes 1) genetic variation within a species, 2) species diversity in different habitats, and 3) ecosystem diversity (e.g., forests, grasslands, wetlands).

Scientific knowledge is best in terms of species diversity. Our knowledge of biodiversity is extremely poor; only 1.8 million species have been identified. Microorganisms are the least known.

Scientific evidence suggests two situations of life on Earth: 1) the vast majority of species have gone extinct and 2) the diversification of life we see today took a long time. It was not until 600 million years ago that it exploded.

Biological diversity is at its pinnacle, despite five major pulses of extinction.

Changes in biodiversity can influence humans' resources such as food, energy, and medicines as well as ecosystem services such as purification and recycling.

Grades 9 – 12

What is the current threat to biodiversity given human impact? How will changes in biodiversity affect humans?

Humans depend on the living world. The resources and benefits provided by the living world are considered "ecosystem services."

Biodiversity results from the formation of new species (speciation) minus extinction.

Biodiversity is seriously threatened by human impact in the form of habitat destruction, over-exploitation, damage by invasive species, and climate change. These have the potential to cause a major pulse of biological extinctions.

Biological extinction is a critical factor in reducing biodiversity because it is irreversible.

Sustaining biodiversity so productivity and ecosystem functioning remain is essential to maintaining and enhancing the quality of life of the growing human population.

Earth and Space Science (ESS) Core Idea 1: Humans are a small part of a vast Universe; planet Earth is part of the Solar System, which is part of the Milky Way galaxy, which is one of hundreds of billions of galaxies in the Universe. [The Solar System, Galaxy, and Universe]

ESS1.A: The Universe

Sub-question: *What is the Universe?*

Earth is one planet of single star in a galaxy of hundreds of billions of stars, and we see hundreds of billions of galaxies extending far in all directions in complex patterns of matter and space. Space in this huge system that we call the observable Universe is expanding, and has been since the Big Bang, a very rapid expansion stage 13.7 billion years ago. All this is known from matching theory and models with multiple threads of observational evidence.

Grades K – 2

What are the furthest objects that we can see?
Things look smaller when they are farther away. Although it looks smaller, the Sun is much bigger than the Earth.

The stars are extremely far away. Most of the points of light in the night sky are huge stars.

Our Sun is a star that appears larger and brighter than all the rest because it is much closer to us than any other star.

Grades 3 – 5

What patterns do we see in the night sky?
Stars appear in fixed patterns in the sky to form what we call constellations. Astronomers use the constellations to map out regions of the sky.

We recognize planets because their position in the sky changes relative to the constellations. A model that fits these observations is that planets are much nearer to us than the stars and orbit around the Sun, as does the Earth.

What do telescopes reveal?
Telescopes reveal features of distant objects, and allow us to see objects that are too faint for the eye to see. They reveal that many of the things that look like stars are galaxies each containing hundreds of billions of stars.

Grades 6 – 8

How can we tell how far away are the stars?
Distances to the closest stars can be measured by parallax as Earth orbits the Sun. For more distant objects comparison of apparent brightness with known intrinsic brightness of certain types of stars and supernovae allows distance estimates.

What are stars?
Stars like our Sun are huge spheres of hot glowing gas. Our Sun is an average-sized star about halfway through its 10 billion-year lifetime.

How big is the Universe?
The Milky Way is one of hundreds of billions of galaxies in the Universe. A sense of comparative sizes of the Earth, Sun, solar system and galaxy begins to give a glimpse of the vastness of the visible Universe.

Grades 9 – 12

What is the large-scale structure and evolution of the Universe?
Distance measurements to thousands of galaxies show they are arranged in clusters and sheets, surrounding vast empty spaces.

We see stars as they were when light left them, in some cases billions of years ago. This allows us to investigate some aspects of the history of the Universe.

Observations of the spectra of galaxies show they are spreading out from each other, indicating that space is expanding. Our observable Universe grew out of a much smaller region starting with an extremely rapid expansion period known as "Big Bang" which occurred 13.7 billion years ago. This theory is supported by observations of the afterglow from the Big Bang in the form of the Cosmic Microwave Background, and multiple other detailed observations.

What will be the fate of the Universe?
Observations indicate that the Universe is expanding at an increasing rate and may expand forever. Nobody knows why.

Earth and Space Science (ESS) Core Idea 1: Humans are a small part of a vast Universe; planet Earth is part of the Solar System, which is part of the Milky Way galaxy, which is one of hundreds of billions of galaxies in the Universe. [The Solar System, Galaxy, and Universe]

ESS1.B: Gravity, Energy, and Matter in the Universe

Sub-question: *What forces and processes govern motion, matter, and structure in the Universe?*

The stars, planets, and galaxies move in patterns controlled by gravity, and were formed by the action of gravity on clouds of gas and dust. Stars radiate energy released by nuclear fusion in their cores and some end their lives as supernovae, thereby producing and distributing material containing all the elements into space.

Grades K – 2

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Grades 3 – 5

What keeps people on the Earth?
No matter where you are on Earth the direction of the pull of Earth's gravity is always toward the center of the Earth.

Why do planets orbit the Sun?
The gravitational pull of the Sun on the Earth and other planets keeps the planets orbiting the Sun.

Why does the Moon go around the Earth?
The Earth's gravity pulls the Moon toward the Earth.

Grades 6 – 8

How has gravity shaped the Universe and kept it in motion?
There are gravitational forces between any two objects. Understanding how these forces depend on mass and distance allows one to model how bodies in space form and affect each others' motions.

Computer simulations show that gravitational forces within a huge cloud of gas and dust would form stars, and smaller clouds would pull together and form planetary systems.

Simulations demonstrate how gravitational attraction between stars formed galaxies, and keeps them in coordinated motion.

Observations of the motion of stars within galaxies can only be explained using known gravity if they contain more mass than can be observed in their stars. We do not yet know what particles compose this "dark matter".

How do stars shine?
Stars shine because of nuclear fusion at its core. A star can exist for millions to billions of years before using up their nuclear fuels.

The biggest and brightest stars burn out fastest and become black holes at the end of their life cycle. Other stars end their lives as white dwarfs or neutron stars.

Earth and Space Science (ESS) Core Idea 1: Humans are a small part of a vast Universe; planet Earth is part of the Solar System, which is part of the Milky Way galaxy, which is one of hundreds of billions of galaxies in the Universe. [The Solar System, Galaxy, and Universe]

Grades 6 – 8

Grades 9 – 12

How do objects go into and stay in orbit?
A spacecraft can be launched and placed into orbit by using a rocket. Natural bodies may change orbits for a number of reasons, such as the gravitational effect of a third body or collisions. The many impact craters seen throughout the solar system record such collisions.

Gradual changes in Earth's orbit and in the tilt of its axis of rotation change the intensity of sunlight falling on Earth over hundreds of thousands of years, causing a cycle of ice ages.

Where did matter in the Universe come from?
Spectra taken of objects throughout the Universe reveal that the objects have a wide variation in temperature, composition and motion, but that the same elements are present and the same physical laws operate everywhere in the Universe.

The matter of our Universe is a remnant from the Big Bang, which produced plasma of protons, neutrons and electrons.

In the hot, dense, early Universe, fusion processes formed small nuclei such as helium and lithium.

How do gravity and nuclear energy determine the evolution of stars?
Matter gains energy as it falls or flows to the center of a star, so this region is hot and dense enough to produce nuclear fusion. Fusion releases outflowing energy that balances the inward gravitational flow and eventually leaves the star's surface as light.

A sequence of fusion processes produces all elements lighter than iron in the core of stars. Once this process completes, gravitational collapse begins and the star enters its end-stage history, the details of which depend on its mass.

Elements heavier than iron are produced when massive stars go through a supernova stage as they collapse. These supernova explosion spread matter containing all the elements through space, leaving a remnant black hole or neutron star.

The elements in our solar system came from earlier generations of stars.

Earth and Space Science (ESS) Core Idea 1: Humans are a small part of a vast Universe; planet Earth is part of the Solar System, which is part of the Milky Way galaxy, which is one of hundreds of billions of galaxies in the Universe. [The Solar System, Galaxy, and Universe]

ESS1.C: Earth and the Solar System.

Sub-question: *What is Earth's relationship to other objects in the solar system?*

Chemical and isotope abundances provide evidence that the solar system and all its planets formed from a vast disk of gas and dust more than four billion years ago. Gravity and the motions of Earth and the Moon relative to the Sun explain many observed patterns here on Earth.

Grades K – 2

How does the Sun affect Earth?
Light from the Sun helps keep Earth's surface warm, gives us light, and allows plants to grow.

How do the Sun and Moon change appearance during the day and night sky?
The Sun appears in different places in the sky during the day. The Moon also appears in different places in the sky.

A small telescope shows that the Moon looks very different when seen "up close." People have walked on the Moon's surface.

Grades 3 – 5

What is the shape of our Earth?
Earth is not flat as it appears, but is shaped like a sphere. Humans have known this for thousands of years from various observations such as the disappearance of objects over the horizon, the different lengths of shadows in different locations, etc.

How does the Earth relate to the Sun and Moon?
A model in which the same scale is used for size as for distance helps us understand the Earth-Sun-Moon system.

A spinning spherical Earth model can be used to explain night and day. The orbit of Earth around the Sun explains why we see different constellations during the year.

Observations of the Moon's regular pattern of phases and a simple physical model illustrate the causes of the Moon's phases and eclipses.

Grades 6 – 8

What causes ocean tides?
Gravitational forces change as the relative positions of neighboring massive objects change. On Earth, daily ocean tides are caused by gravitational attractions of the Sun and the Moon as the Earth rotates. Regular week-to-week changes in tidal patterns reflect the changing configuration of the Sun-Moon-Earth system.

Are there other planets that can support life?
No one knows if life exists on other planets. However, observations and models suggest that conditions for life (primarily liquid water) once existed on Mars and may still exist on moons of Jupiter and Saturn. Someday people or robots may be able to examine those places for signs of life.

Telescopic observations of distant stars provide strong evidence that many of them have planets and that new planetary systems are still forming. Astronomers are searching for possible conditions for and signs of life in distant planetary systems.

Grades 9 – 12

How did our solar system form?
Orbiting telescopes have found disks of gas and dust surrounding new stars, providing support for the theory that our solar system formed from such a cloud. The age for the formation of the solar system 4.6 billion years ago is shown by radioactive dating of meteorites and other ancient materials.

Telescope observations and space probes reveal four rocky inner planets (including Earth) close to the Sun, four much larger planets consisting mostly of dense gases further from the Sun, and countless smaller bodies (dwarf planets, moons, asteroids, comets, and meteoroids). Their formation process is still being investigated.

Many of the geologic processes that operate on Earth are seen to be operating on other planets or their moons.

The solar system changes as comets, asteroids, and meteoroids impact the planets, including Earth.

What causes seasons?
The Sun's path across the sky changes during the year so that length of day and the rate of incoming solar energy per unit of area changes at any given place, causing warmer and cooler seasons. This can be explained by a model in which Earth's axis is tilted with respect to its plane of rotation around the Sun.

ESS Core Idea 2: Earth is a complex and dynamic 4.6-billion-year-old system of rock, water, air, and life. [Earth's Planet-sized Structures, Processes and History]

ESS2.A: Continental Drift, Plate Tectonics and Earth's Internal Heat

Sub-question: *What changes the positions of the continents over time?*

Tectonic plates move across the Earth's surface, carrying the continents, creating and destroying ocean basins, setting off earthquakes and volcanoes, and pushing up mountain ranges. World maps show these features and their relationships. These plates are the top parts of giant convection cells that bring hot materials from the deep mantle up to the surface to cool off then fall back in.

Grades K – 2

What is an earthquake and why does it happen?
When the ground shakes, we say we are having an earthquake. The shaking comes from a place where rocks under the ground have been bent or squeezed so much that they break.

How are the continents and oceans arranged on the surface of the Earth?
The world map shows large areas of dry land which we call continents, while other parts of our planet are covered with water in the oceans. The continents and oceans have different shapes and sizes.

What is a volcano and why do volcanoes happen?
A volcano is a place where super-hot melted rock comes out of the ground and freezes on the surface. This melted rock comes up from inside the Earth where it is so hot that even the rocks can melt.

Grades 3 – 5

What does the global pattern of earthquake locations show us about the Earth's tectonic plates?
The Earth's surface is divided into a number of large rigid plates which are moving slowly across the Earth's surface. Most earthquakes occur along the plate boundaries where the plates push against each other.

What do the shapes and arrangements of the continents and oceans suggest about their histories?
Earth's continents move slowly across the surface of the planet. They are embedded in the tops of the moving tectonic plates.

The shapes of our present continents can be fit together like pieces of a puzzle. This is part of the evidence that tells us that most of the continents were once joined together in a large super-continent.

Grades 6 – 8

How does thermal energy move around, heating and cooling objects and places?
Energy flows out of hotter regions or objects and into colder ones, in three ways: conduction, convection, and radiation (link to PS2.A)

What drives plate tectonics?
Both temperature and pressure increase greatly from the Earth's surface to the core. Earth's thermal energy flows from the hot interior toward the cooler surface and then radiates out into space. This heat moves largely through the convection of hot mantle materials, but also through conduction and radiation. Convection within the solid mantle drives the many processes of plate tectonics.

What happens when tectonic plates pull apart?
Where plates pull apart, the ground cracks open making earthquakes and hot molten rock rises to fill the crack as it cools. All of the world's ocean floors were made by this process, called ocean floor spreading. Spreading is presently happening along the mid-ocean ridges and in some continental rifts.

What happens when tectonic plates collide?
As an oceanic plate runs into a continental plate, it dives under it, falling back down into the Earth's mantle. This process is called subduction. The world's largest earthquakes happen when a subducting plate gets stuck against its overriding plate, then suddenly breaks loose. The world's deepest trenches are found where the subducting plates are bending down to start their descent into the mantle.

When two continents collide, they smash into each other, folding up their fronts to form mountain ranges. The world's tallest mountains are found along plate boundaries where continental plates are colliding. Older, worn-down mountain ranges are often the remnants of ancient plate collisions.

What if two plates just move sideways past each other?
When this happens, the plates simply slip past each other, sometimes smoothly, sometimes in jerks during earthquakes. The San Andreas fault is where the Pacific plate slips sideways past the North American plate. Transform faults are also extremely common along the mid-ocean ridges.

How can we know the locations and kinds of plate boundaries on Earth and is there a plate boundary near my area?
By comparing world maps of ocean depth, continental mountain belts, and earthquake and volcano locations, we can locate and characterize most of the world's plate boundaries.

ESS Core Idea 2: Earth is a complex and dynamic 4.6-billion-year-old system of rock, water, air, and life. [Earth's Planet-sized Structures, Processes and History]

Grades 6 – 8

Grades 9 – 12

Why and how does Earth's solid mantle convect?

Earth, like all planets, is cooling off over time as heat radiates out into space from Earth's surface.

Radioactive decay of long-lived but unstable isotopes continuously generates thermal energy within Earth's crust and mantle. Our planet would be geologically inactive without this internal energy generation. This energy moves through and out of Earth's interior, largely through convection of hot materials.

Global Positioning Satellites show that the tectonic plates move with respect to one another at speeds of up to 10 cm/year. Though Earth's mantle is extremely thick and stiff, it flows, though very slowly, at rates of centimeters per year. Plate tectonics can be viewed as the surface expression of mantle convection.

How do we know that all the deep ocean floors were made by sea floor spreading?

Maps made from ship and satellite data show that the ocean floors have very distinct topographic patterns. The mid-ocean ridges have linear rifts and ridges perpendicular to the spreading direction; these are broken and offset by other ridges and troughs that lie parallel to the spreading direction along transform faults.

Why does Earth have a magnetic field and how does it help us?

The Earth has a dipole magnetic field, much like that of a bar magnet. It is generated by convection in the liquid iron outer core, along with Earth's rotation around its axis. The direction of this bar magnet flips occasionally on geologic time scales.

Magnetic compass readings of the field's north-south orientation help humans navigate around present day Earth.

Rock records of ancient magnetic field directions help scientists determine the history of continental drift and ocean floor spreading.

By deflecting the solar wind around the planet, Earth's magnetic field prevents solar wind from stripping away Earth's atmosphere.

How do continents change over time?

Continents are continually shaped and reshaped by competing constructive and destructive forces. They grow in volume by the addition of magmas from the mantle, the deposition of platform sediments, and lateral accretion of other continental pieces; they shrink in volume and area by erosion and lateral compression in mountain belts.

North America has gradually grown in size over the past four billion years through a complex set of interactions with other continents, including the accretion of many crustal pieces.

ESS Core Idea 2: Earth is a complex and dynamic 4.6-billion-year-old system of rock, water, air, and life. [Earth's Planet-sized Structures, Processes and History]

ESS2.B: Earth's Materials

Sub-question: *What is planet Earth made of?*

Earth is made of rock, metal, water, air, and living organisms in the form of the geosphere, hydrosphere, atmosphere, and biosphere.

Grades K – 2

What are rocks and minerals?
Rocks and minerals are solid and occur naturally. Minerals have observable characteristics, such as how hard they are, the way they shine, and sometimes their color. Rocks are made of mineral crystals, often too tiny to see.

Where does the soil come from?
Soil comes from the disintegration of rock into sand and clay. Soil contains not only sand and clay but also decayed plants and many living organisms.

Grades 3 – 5

What would you see if you could travel to the center of the Earth?
Earth is made of different materials that form onion-like layers. The heaviest materials form the center of the Earth and the lightest materials are at Earth's outer edge.

Earth's core is chiefly iron. Surrounding the iron core are the mantle and crust, both made of rock. On top of the crust are the water of the ocean and the air of the atmosphere.

Where are the oceans found?
Ocean water fills up all the low parts of Earth's surface, the ocean basins, and often laps onto the edges of the land as well (continental shelves). All the oceans of the Earth (Pacific, Atlantic, Arctic, Indian) are interconnected, so that they are really one global ocean. Water circulates throughout the global ocean.

What is air?
Air is a mixture of gases, mostly nitrogen and oxygen, that surrounds us, and moving air is called wind.

Grades 6 – 8

Why do Earth Scientists develop models to represent Earth?
Scientists probe the Earth's interior with seismic waves and other measurement tools, and model the Earth and its processes, modifying the models until they can explain the observations.

Why are there volcanoes?
Though the mantle is almost entirely solid, local conditions can cause small amounts of mantle rock to melt and form magma. Magma is less dense than the rocks around it, so it rises up to the Earth's surface. Some gets trapped under the surface and freezes slowly to form rocks with big crystals (e.g. granites) and some of it reaches the surface and erupts to form volcanoes.

Where is Earth's water found?
Nearly all of Earth's available water is in the ocean. Most of the freshwater is found underground as groundwater or as glaciers, streams, lakes, and wetlands. Only a tiny fraction of water is found in the atmosphere, but this helps to control the temperature of Earth's surface.

Grades 9 – 12

Why is water important?
Water is essential for life on Earth. Earth is unique in our Solar System in that water has coexisted at Earth's surface in three phases (solid, liquid, and gas) for billions of years, allowing the development and continuous evolution of life.

What is in our atmosphere?
Earth's atmosphere is a mixture of gases with small quantities of liquid and solid particles. Earth's atmosphere is mostly nitrogen and oxygen gases, but small traces of water vapor and carbon dioxide play important roles in Earth's systems.

Combining observations from satellites and weather balloons with known physical and chemical behavior of gases, we can model the atmosphere as a series of layers; different layers have different compositions and temperatures. The lower part of the atmosphere contains and controls Earth's weather. An important upper layer of the atmosphere called the stratosphere contains ozone, which protects Earth's surface life by absorbing ultraviolet solar radiation.

What is the biosphere?
The biosphere includes Earth's life, which can be found in many parts of the geosphere, hydrosphere, and atmosphere. Life occupies all of Earth's varied environments, including extreme environments [deep underground within rocks; within glacial ice; at seafloor vents where hot fluids escape from the oceanic crust].

ESS Core Idea 2: Earth is a complex and dynamic 4.6-billion-year-old system of rock, water, air, and life. [Earth's Planet-sized Structures, Processes and History]

ESS2.C: Earth's History

Sub-question: *How old is Earth and how do we know the timing of events in its history*?

Earth's rocks and other materials provide a record of its 4.6 billion-year-old history.

Grades K – 2

Were fossils once living?
Rocks are not living. However, fossils are made from things that were *once* living, usually long before there were people.

Grades 3 – 5

How old is Earth?
Earth is 4.6 billion years old and life began almost 4 billion years ago. Thus, both Earth and life have developed over a HUGE expanse of time. Millions and billions of years are nearly impossible to comprehend from a human time perspective.

When it first formed, Earth's surface was very different from the way it is now.

Some meteorites are the oldest rocks found on Earth's surface, many having formed at the start of the solar system.

How far back does the Earth's rock record go?
While the total record of Earth's events extends back over billions of years; in any one place, the local rock patterns record only a small section of Earth history, from a few years to many millions of years. Thus, Earth's history can be reconstructed by combining information from many different places.

What are the ages of the rocks in your area?

Grades 6 – 8

How do scientists determine Earth's history?

Earth scientists use the structure, sequence, and properties of rocks, sediments, and fossils to reconstruct events in Earth's history. Because many individual species existed alive for limited periods of time and then became extinct, fossil content provides approximate periods in which the rocks were formed.

The geologic time scale is a way to organize Earth's history, largely based upon the fossil record with special attention to times of mass extinctions of life. The dates derived from fossils alone only give us relative dates - one organism lived earlier or later in time than another. Other methods must be used to figure out the absolute dates (in millions or billions of years) of events in the timescale.

Grades 9 – 12

What can we learn about geologic history from examining Earth's rock record?
Over Earth's vast history, both gradual and catastrophic processes have produced enormous changes. Many changes in Earth systems are not observable over human time spans but are clearly recorded in the rock record.

The timing of changes can be described in relative terms (observed sequential patterns) or absolute terms (measured ages in number of years). Relative ages can be established using fossils (evolution and extinction of organisms) and using rock relationships (one sedimentary bed deposited on top of another older layer, igneous rocks intruded into pre-existing older rocks, etc.). Absolute ages are most commonly obtained by measuring how much of a radioactive isotope in the rock has decayed since the rock was formed. Some other absolute dating methods use tree rings and sedimentary records of rhythmic climate changes.

Why are other objects in the solar system used to determine Earth's early history?
On Earth, active geologic processes such as plate tectonics and erosion have destroyed or altered most of the early rock record, but many other objects in the solar system have changed little over billions of years. Study of these objects allows us to learn about events that happened in the early solar system, including the formation of planet Earth.

ESS Core Idea 3: Earth's surface continually changes from the cycling of water and rock driven by sunlight and gravity. [Earth's Surface Processes and Changes]

ESS3.A: The Roles of Water in Earth's Surface Processes

Sub-question: *How do the properties and movements of water affect Earth's systems?*

Water's unique properties play critical roles in many Earth systems. Solar energy and gravity drive the movements of water known as the water cycle

Grades K – 2

Where is water found on Earth?
Water is found in lots of places: in the oceans, in lakes and rivers, underground, and in the air.

Where does the rain come from?
Rain, snow, hail, etc. come from clouds in the sky.

Grades 3 – 5

How is water special?
Water is one of very few substances that can be solid, liquid or gas under everyday conditions at Earth's surface.

How are the rain, rivers, and ocean connected?
When energy from the Sun warms liquid water in the ocean, some of it turns into a gas (water vapor) in the air. When that air is cooled, some of the water vapor condenses back into a liquid (fog and cloud, or rain droplets) or a solid (snow flakes). Rain and snow falls back to the surface and the water runs down rivers back to the ocean.

Grades 6 – 8

Why does ice float?
Water in solid form is less dense than as a liquid, the reverse of most materials. This property has many important consequences for Earth systems (e.g. surface freezing of lakes, glacial movement).

Where is water found and what drives its movement across Earth's surface?
Water is found almost everywhere on Earth, from high in the atmosphere (as water vapor) to low in the atmosphere (as droplets or snowflakes in clouds) to the mountain snow caps and glaciers (solid) to running water on the land and in the global ocean (liquid) and underground (liquid).

The movements of water and its changes in form are primarily driven by sunlight and gravity. Sunlight causes evaporation off of the ocean surface and drives atmospheric circulation that transports the water vapor around the globe. When water-vapor laden air cools, water condenses forming clouds and fog, and eventually falls back to the surface by the force of gravity, where it either returns to the atmosphere through evaporation or transpiration or, if it fell on the land, flows downward to the ocean in streams, glaciers, or through the ground. This repeating chain of events is known as the Water Cycle.

Grades 9 – 12

How do water's unique properties control Earth's surface processes?
Earth is often called the water planet, both because of the abundance of liquid water on its surface and because water's unique combination of physical and chemical properties are essential to the dynamics of most of Earth's systems. These properties include water's exceptional ability to absorb, store, and release large amounts of thermal energy as it changes state, to reflect sunlight, to expand upon freezing, to dissolve many materials, and to lower the viscosity and melting point of rocks.

How does the ocean system operate?
The ocean consists of an interconnected circulation system powered by wind, tides, Earth's rotation (Coriolis effect), the Sun, and water density differences. The shapes of ocean basins and adjacent land masses influence the paths of circulation.

The ocean's temperature and salinity vary with depth and location, and control the wide variety of ocean ecosystems.

ESS Core Idea 3: Earth's surface continually changes from the cycling of water and rock driven by sunlight and gravity. [Earth's Surface Processes and Changes]

ESS3.B: Formation and alteration of rocks and landforms

Sub-question: *How does matter cycle on Earth's surface over time?*

Earth's surface materials are continually moved around and changed from one form to another, by the action of water, ice and plate motion.

Grades K – 2

What moves rocks and soil?
Sand, soil, and rocks sometimes move from one place to another. They can fall down a hill, and they can be moved by running water and by wind.

Grades 3 – 5

Why don't the rocks in buildings and mountains last forever?
The process of weathering breaks down rocks into sand and mud. The process of erosion removes rock and sediment from one location and moves it to another. Erosion is caused by water, ice and wind, and by gravity, which pulls everything downhill.

Grades 6 – 8

How do geologic processes change rocks from one form to another?
Rocks can form from the cooling of molten rock, the accumulation and consolidation of sediments, and the alteration of older rocks by heat, pressure, and fluids. These three processes form igneous, sedimentary, and metamorphic rocks.

How do geologic processes reshape landforms?
Streams, glaciers, wind, and waves erode rocks and transport the sediments to lower elevations, ultimately to be deposited in the ocean.

Tectonic and volcanic processes create mountains and plateaus, while weathering and erosion wear them down and remove them.

How do ocean waters affect the history of much of the land?
Shoreline waves are powerful agents of erosion while shoreline currents are constantly moving loose materials along the coast and offshore. Over millions of years, shorelines move back and forth across continents by hundreds of kilometers as sea levels rise and fall by hundreds of meters due to climate changes. The deep interiors of continents, now far from the ocean, often show a history of ancient shoreline erosion and seabed deposition.

Grades 9 – 12

How is a rock at Earth's surface destroyed or changed over time?
Near surface rocks all undergo weathering. Most weathering occurs chemically, underground and in the presence of water, causing disaggregation of crystalline rocks to form sand and clay. Mechanical weathering also can occur through a variety of processes such as frost wedging, plant growth, exfoliation, abrasion, and changes in temperature.

If a rock experiences increases in pressure or temperature, through burial or by heating from magmas, its structure can be reorganized and new crystals can grow, forming a metamorphic rock.

How does gravity control the appearance of the land?
Earth's materials are continuously being pulled downhill by gravity. This can occur rapidly (landslides, avalanches) or slowly (creep).

The downward flow of water shapes landscapes through erosion, transport, and deposition. Water participates in both the dissolution and formation of Earth's materials.

Ice is an especially powerful agent of weathering and erosion when it moves as part of a glacier. Moving of glaciers can pick up and move loose debris, including huge rocks, great distances. They can scour and polish land surfaces and grind rocks to powder. Glacial ice covered and altered vast areas of some continents during the Ice Ages.

How do Earth's surface systems interact?
Earth's climate and plate tectonic systems are dominated by the unique physical and chemical properties of water. They are dynamic, changing through geological, hydrological, physical, chemical, and biological processes. These systems interact over a wide range of temporal and spatial scales: from microscopic to global in size and over fractions of a second to billions of years. As a result, components of Earth's surface systems may appear stable, change slowly over long periods of time, or change abruptly with catastrophic consequences for living organisms.

Changes in part of one of Earth's systems can cause new changes to that or other systems. These changes may take the form of "feedbacks" that can increase or decrease the original changes in unpredictable and/or irreversible ways.

ESS Core Idea 3: Earth's surface continually changes from the cycling of water and rock driven by sunlight and gravity. [Earth's Surface Processes and Changes]

ESS3.C: Weather and Climate

Sub-question: *What regulates weather and climate?*

Weather and climate are regulated by complex interactions among the components of the Earth's system, and change over varying time scales.

Grades K – 2

What is weather and how do we describe it?
Weather is the condition of sun, wind, snow or rain and temperature in a particular region at a particular time. We measure these conditions to describe and record the weather.

Weather changes from day to day, but in any particular place it follows a similar pattern year to year. That pattern is called the climate of that place.

Grades 3 – 5

How do scientists predict the weather?
Scientists use measurements of the atmosphere collected at land stations and by satellites to predict the weather.

Scientists compare current observations with models based on past weather patterns to make a weather prediction.

What is the difference between weather and climate?
Weather is the minute-by-minute variable condition of the atmosphere on a local scale. Climate is a conceptual description of an area's average weather conditions and the extent to which those conditions vary over the year.

Grades 6 – 8

What factors control Earth's weather and climate?
Weather and climate are influenced by interactions involving the Sun, ocean, atmosphere, clouds, ice, land, and life. These influences vary with latitude, altitude and the unique shapes of continents and landforms, all of which affect ocean and atmospheric flow patterns.

The ocean exerts a major control on weather and climate by dominating Earth's energy and water cycles. It absorbs and stores large amounts of solar energy, releasing it very slowly so that it moderates and stabilizes coastal climates. Thermal energy is redistributed globally through ocean currents (e.g. the Gulf Stream).

Water vapor and thermal energy are also moved around by circulation in the atmosphere. Energy from the Sun heats the atmosphere, causing differences in air pressure. In general, winds in the atmosphere blow from regions of high pressure to regions of low pressure, but patterns of circulation in Earth's atmosphere can occur at many different spatial scales, from local to global. Temperature differences, Earth's rotation, and the configuration of continents and oceans establish the large-scale atmospheric circulation.

Storms often occur when air masses of differing temperatures collide, causing the warmer air to rise over the colder air. As the warmer air rises, it cools, causing condensation and precipitation.

The amount and style of precipitation varies hugely from place to place on the land. Most water vapor evaporates from the oceans, so precipitation is much greater where the prevailing winds come from the ocean; continental interiors, far from oceans, tend to be dry. When winds encounter mountains, the air rises, cools, and forms clouds, so that the windward sides of mountains are extra wet and the leeward sides dry (the Rain Shadow Effect).

What is the Greenhouse Effect?
The Greenhouse Effect keeps Earth's surface warm. Greenhouse gases [water vapor; carbon dioxide; methane; nitrous oxides] absorb and hold energy radiating from Earth's surface, insulating the planet. Without this phenomenon, the Earth would be too cold to be habitable.

ESS Core Idea 3: Earth's surface continually changes from the cycling of water and rock driven by sunlight and gravity. [Earth's Surface Processes and Changes]

Grades 6 – 8

Grades 9 – 12

How does climate change over space and time in response to both natural and man-made causes?

Climate change is a significant and persistent change in an area's average climate conditions or their extremes. Global Climate is a dynamic balance of energy inputs from the Sun and the reflection, absorption, storage, re-distribution and re-radiation of this energy in the atmosphere and ocean and at land surfaces, on many different time scales. Positive feedback loops can amplify impacts of these effects and trigger relatively abrupt changes in the climate system.

Climate changes over many millions of years are dominated by the changing configuration of continents and erosion rates of mountains. Climate variations over many thousands of years, like the Ice Ages, are primarily driven by changes in Earth's orbit around the Sun and the tilt of Earth's axis of rotation.

Natural factors that cause climate changes over human time scales (tens or hundreds of years) include volcanic activity and changes in ocean circulation patterns, atmospheric composition, and the output of energy from the Sun. When ocean currents change their flow patterns, such as during El Nino conditions, some regions become warmer or wetter while others become colder or drier.

Small increases in the atmospheric concentration of carbon dioxide and other greenhouse gases tend to increase the capacity of the Earth to retain heat, while clouds and volcanic ash in the atmosphere tend to decrease the amount of solar heat that can enter the system.

Objects of different temperatures emit radiation at different wavelengths. The surface of the Sun primarily emits visible light; the surface of Earth primarily emits infrared radiation. Greenhouse gases in the atmosphere preferentially absorb radiation of different wavelengths, allowing sunlight to freely pass inward but inhibiting the passage of infrared radiation outward, and thus keeping Earth's atmosphere and surface warm.

How do global climate models predict future climate change?

Complex computer programs called Global Climate Models that incorporate many factors [including solar inputs, Earth's orbit, ocean circulation, volcanic activity, glaciers, vegetation, and atmospheric composition] are used to model and predict climate change.

These models predict that future regional climate changes will be very complex and varied but that average global temperatures will continue to rise. Some areas are predicted to get more warming than average while a few are predicted to get cooler.

The outcomes of Global Climate Models strongly depend upon the amounts of human-generated greenhouse gases added to the atmosphere each year and hence the outcomes depend on human choices.

ESS Core Idea 3: Earth's surface continually changes from the cycling of water and rock driven by sunlight and gravity. [Earth's Surface Processes and Changes]

ESS3.D: Biogeology

Sub-question: *How does life interact with Earth's other systems*?

Life evolves on a dynamic Earth and continuously modifies the planet, and is modified by changes in the planet.

Grades K – 2

Why do plants and animals live where they do?
Plants and animals depend upon the resources and conditions of their habitats to survive.

Grades 3 – 5

How are plants and animals interconnected with their environments?

Living organisms are integral parts of ecosystems, affecting and affected by the physical characteristics of their regions.

Grades 6 – 8

How does life affect Earth's geology?
Life changes the physical and chemical properties of Earth's geosphere, hydrosphere, and atmosphere.

Plants and micro-organisms produced most of the oxygen in the atmosphere through photosynthesis, allowing the existence of animals, and providing the substance of fossil fuels and many sedimentary rocks. Some oxygen becomes ozone, which protects life at Earth's surface from harmful UV radiation.

Microbes change the chemistry of the Earth's surface and play a critical role in nutrient cycling (such as carbon and nitrogen) within most ecosystems.

How does Earth's geology affect life?
Ecosystems provide the resources and processes necessary to sustain the biosphere.

Changes in environmental conditions affect the survival of individual organisms, populations, and entire species.

Almost all food-derived energy comes originally from sunlight, but there are environments such as mid-ocean ridges and other volcanic regions where the energy source comes from the Earth.

Evolution, including the origination and extinction of species, is a natural and ongoing process. As an outcome of dynamic Earth processes, life has continually evolved to new forms as they adapted to new environments.

Grades 9 – 12

How does life affect Earth's climate?
Greenhouse gases in the atmosphere are controlled by biogeochemical cycles that continually move these gases among the ocean, land, life, and atmosphere reservoirs.

Life is a major driver of the global carbon cycle and influences global climate by modifying the chemical makeup of the atmosphere.

The abundance of carbon in the atmosphere is reduced through seafloor accumulation of marine sediments and accumulation of plant biomass and is increased through processes like deforestation and the burning of fossil fuels.

How has geology affected the evolution of life?
Individual organisms survive within specific ranges of temperature, precipitation, humidity, and sunlight. Species exposed to climate conditions outside their normal range must adapt or migrate, or perish.

More complex life forms and ecosystems have arisen over the vast expanse of Earth's history, adapting to new and changing habitats.

Mass extinctions occur when global environmental conditions change faster than large numbers of species can adapt. Mass extinctions are often followed by the origination of many new species over millions of years as surviving species evolve and fill vacated niches.

The life forms that exist today are a result of the history of mass extinctions. Had this history been different, modern life forms including humans might never have evolved.

ESS Core Idea 4: Human activities are constrained by and, in turn, affect all other processes at Earth's surface. [Human Interactions with Earth]

ESS4.A: Natural Hazards

Sub-question: *How do natural hazards affect humans?*

Hazards resulting from natural Earth processes can cause both sudden and gradual changes to Earth's systems that sometimes adversely affect humans. Certain hazards are more likely in some places than others; understanding the human risks is important for the preparation and response to these hazards.

Grades K – 2

What are some forms of severe weather and how do we stay safe during severe weather?
Severe weather can occur in the form of hurricanes, tornadoes, blizzards and ice storms, droughts, and floods. Some of these are more likely than others to happen in your region.

Weather scientists can forecast severe weather and communities can prepare for and respond during these events.

Grades 3 – 5

What kinds of natural hazards affect humans?
A variety of hazards result from natural Earth processes.(e.g. earthquakes, tsunamis, volcanic eruptions, extreme weather, coastal erosion). Humans cannot eliminate natural hazards, but can engage in activities that reduce their impacts.

Loss of life and economic costs can be reduced by identifying high-risk locations and minimizing human habitation and activities in them, improving and regulating construction, developing warning systems, and by community preparedness and response.

Grades 6 – 8

Can earthquakes and volcanic eruptions be predicted?
By tracking the upward movement of magma, volcanic eruptions can often be predicted with enough advance warning to allow regions to be evacuated. The lava and ash erupted from volcanoes can adversely affect communities in many different ways. In some cases the lava from volcanic eruptions creates new land.

Earthquakes occur suddenly and usually without notice, and the specific time, day or year cannot be predicted. However, the history of earthquakes in a region and mapping of fault lines can help forecast the likelihood of future events. Though most earthquakes occur at tectonic plate boundaries, they are capable of occurring anywhere. Earthquakes cause damage through the accelerations of the ground surface as well as the landslides, tsunamis, ground liquefaction, and fires that they trigger.

How does severe weather affect humans?
Severe weather can cause sudden, dramatic damage to individuals, property, infrastructure, and ecosystems. Longer term impacts can be both positive and negative.

Grades 9 – 12

How do geologic events affect civilization?
Natural hazards and other geologic events have shaped the course of human history. These events can significantly alter the size of human populations and drive human migrations. Risks from natural hazards increase as populations increase and expand into vulnerable areas.

Natural hazards can be local, regional, or global in origin. Local events can have distant impacts because of the interconnectedness between human societies and Earth's systems. Human activities can contribute to the frequency and intensity of some natural hazards.

A range of natural records shows that the last 10,000 years have been an unusually stable period in Earth's climate history. Modern human societies developed during this time. The agricultural, economic, and transportation systems we rely upon are vulnerable if the climate changes significantly.

ESS Core Idea 4: Human activities are constrained by and, in turn, affect all other processes at Earth's surface. [Human Interactions with Earth]

ESS4.B: Natural Resources

Sub-question: *How do humans depend upon Earth's materials?*

Humans depend upon Earth for many different resources, including air, water, soil, rocks, minerals, metals, and sources of energy.

Grades K – 2

Where do natural resources come from and how do we use them?

Natural resources are raw materials that we obtain from the environment. People use natural resources in many different ways in their homes and businesses.

Grades 3 – 5

What natural resources do we use for drinking, for growing food, and for generating energy?

Our fresh drinking water comes from streams, lakes, dams, melting glaciers, and groundwater.

Soil contains water and small amounts of certain nutrients that plants need to grow.

People get energy from a combination of many different renewable and non-renewable sources.

Grades 6 – 8

Where do we get the mineral and energy resources needed to construct and run our civilization?

Humans depend on Earth's land, ocean, and atmosphere for many different resources. Some of these resources are renewable over human lifetimes and some are non-renewable.

Mineral resources are limited. Many are nonrenewable on human time scales and, at the present rates of usage, many will run critically low in the near future. Mineral resources are distributed unevenly around the planet, a result of how and where geologic processes have occurred in the past.

Fossil fuels and uranium currently provide most of our energy resources. Fossil fuels like coal, oil, and natural gas are originally derived from solar energy, but take tens to hundreds of millions of years to form so are non-renewable on human time scales. They are likely to remain the dominant energy source for years to come, but they are becoming increasingly difficult to find and extract.

Oil and natural gas are also used to make numerous products like plastics, textiles, medications, and fertilizers.

Renewable energy resources such as solar, wind, hydroelectric, biomass, and geothermal, and the technologies to exploit them are being rapidly developed.

Why are soil and water considered to be limited resources when they are so common on Earth?

Soil can take many thousands of years to form. Historically, much soil was lost as a result of human agricultural practices that amplify natural erosion processes. Modern soil conservation methods are increasing the protection and preservation Earth's soil, but continual attention should be given this problem.

There are vast amounts of water in the ocean, but humans cannot drink salt water. Only a small amount of Earth's water is fresh, and humans get most of their water from streams, lakes, and groundwater. These sources are constantly renewed by rain and snow, but shortages arise when use exceeds supply or when fresh water is contaminated.

ESS Core Idea 4: Human activities are constrained by and, in turn, affect all other processes at Earth's surface. [Human Interactions with Earth]

Grades 6 – 8

Grades 9 – 12

How has resource distribution affected civilization?
Materials important to modern technological societies are not uniformly distributed around the Earth [oil in the Middle East; gold in California]. Most elements exist in the crust at concentrations too low to be extracted, but geologic processes have concentrated them to economically viable levels in some locations.

Resource availability has guided the development of human society, which has historically populated regions that are geologically advantageous to commerce, food production, and other aspects of civilization.

What sources of energy generation provide options other than fossil fuels?
Renewable energy includes direct solar power, wind, hydroelectric, and biomass. Technologies to exploit these are improving; they are likely to provide an increasing fraction of power generation in future years.

Geothermal energy is also a potential power resource in certain geologically active regions.

Nuclear fission provides an energy source (from uranium) that does not produce carbon dioxide and has ample available resources. It produces radioactive waste products.

All forms of energy production, and other resource extraction, have associated economic, human, environmental and geo-political costs and risks, as well as benefits. New technology and regulation can change the balance of these factors.

Future energy supplies will likely come from a combination of many sources.

ESS Core Idea 4: Human activities are constrained by and, in turn, affect all other processes at Earth's surface. [Human Interactions with Earth]

ESS4.C: Human Impacts on the Earth

Sub-question: *How do humans change the Earth*?

Humans have become one of the most significant agents of geologic change at Earth's surface. The activities that have built human civilizations have both positive and negative consequences related to the sustainability of these civilizations.

Grades K – 2

How can humans protect Earth's resources and environments?

There are many things that people can do to help protect Earth's resources and environments, such as reducing the amount of materials they use, reusing materials when possible, and recycling materials.

Grades 3 – 5

How do human activities pollute Earth and how might they change their activities to reduce this pollution?

Human activities [everyday life; agriculture; industry] can cause pollution of the land, ocean, streams, air, and even outer space.

Modest changes in individual and societal activities can significantly reduce pollution.

Grades 6 – 8

How do human activities alter Earth?

Most actions that change the Earth's environments have both costs and benefits.

Humans affect the quality, availability, and distribution of Earth's water through the modification of streams, lakes, and groundwater. Pollution from sewage runoff, agricultural practices, and industrial processes can reduce water quality. Use of water for industry and agriculture may reduce drinking water availability.

Large areas of land, including delicate ecosystems such as wetlands, are being transformed by human agriculture and land development.

Human activities cause land erosion that exceeds all natural processes. These activities include plowing, urban construction, removal of vegetation, surface mining, and stream diversions, and increased rain acidity.

Extraction of mineral resources and fossil fuels changes landscapes and often has significant side-effects.

Burning of fossil fuels has changed the fraction of carbon-dioxide in the atmosphere significantly in the past 100 years.

Human activities have significantly altered the biosphere, destroying many natural habitats and causing a huge decline in biodiversity.

Grades 9 – 12

How can humans exist sustainably and indefinitely on Earth?

Human populations are increasing. As human populations and per capita consumption of natural resources increase, so do the rates of our impacts on Earth.

Human sustainability requires responsible management of natural resources. Scientists and engineers contribute by developing new technologies to extract resources while reducing the pollution, waste, and ecosystem degradation and by using recycled materials.

Some negative effects of human activities are reversible with proper management; for example, regulations on water and air pollution have greatly reduced acid rain and stream pollution, and regulations on the use of certain gases have halted the growth of the annual ozone hole over Antarctica.

Alternate energy sources can continue to be developed, reducing the environmental impacts of using fossil fuels.

ESS Core Idea 4: Human activities are constrained by and, in turn, affect all other processes at Earth's surface. [Human Interactions with Earth]

ESS4.D: Global Climate Change

Sub-question: *How will global climate change affect humans*?

Climate change, driven by both natural and human activities, has large consequences for all of Earth's surface systems, including humans. Humans can take actions to reduce climate change and its impacts.

Grades K – 2

[Intentionally left blank]

Grades 3 – 5

What will happen to life on Earth if temperatures continue to rise?
Earth's global mean temperature has risen significantly over the past 100 years. If this continues, the lives of humans and other organisms will be impacted in many different ways, both positive and negative.

Grades 6 – 8

How do human activities alter Earth's climate?
Earth's average temperature is now warmer than it has been for at least the past 1,000 years. Much of the observed increase in global average temperatures in the past 100 years is likely due to human activities.

Humans alter global climate patterns by burning fossil fuels, releasing chemicals into the atmosphere, reducing forest cover, and by the rapid expansion of farming, development, and industrial activities.

Global climate change is causing changes in many biological systems, including a decrease in biodiversity and a diminishing of the capacity of some environments to support life.

Sea levels are rising due to both glacial melt and ocean water expansion due to heating. As global temperatures continue to increase, sea levels will rise, causing flooding of coastline areas.

Global climate change will have significant regional variations, viewed positively in some regions and negatively in others.

How can humans reduce climate change and minimize its negative effects?
Humans may be able to mitigate climate change or lessen its severity by reducing greenhouse gas concentrations through processes that move carbon out of the atmosphere or reduce greenhouse gas emissions.

Actions can be taken by individuals, institutions, communities, and governments that influence climate. Reducing human vulnerability depends on understanding climate science and using that knowledge in decisions and activities of human society.

Grades 9 – 12

How might global climate change affect humans?
As global average temperature rises, melting of ice sheets and glaciers, combined with the thermal expansion of warming seawater, will cause sea levels to rise, flooding islands and low-lying lands, contaminating coastal fresh water sources, and increasing damage to homes and businesses from storm surges.

Changing precipitation patterns and temperature conditions are likely to alter the distribution and availability of freshwater resources, reducing access to water for many people.

Incidents of extreme weather are projected to increase as a result of ocean temperature changes. Rain and snow may become less frequent but more intense in many areas; droughts and forest fires may become more frequent where precipitation decreases.

As carbon dioxide levels in the atmosphere rise, ocean water becomes more acidic, threatening the survival of shell-building marine species and the food webs of which they are a part.

Ecosystems will be disturbed by climate change; animals, plants, bacteria, and viruses are likely to migrate to new areas or become extinct.

Drought-reduced crop yields, degraded air and water quality, and increased hazards in coastal and low-lying areas will contribute to increasingly unhealthy conditions for many populations

Geological records of past climates show that climate shifts can occur quite rapidly when certain positive-feedback "tipping points" are reached.

What can be done to reduce global climate change and its negative impacts?
Measurements of greenhouse gas emissions and other factors that drive climate change are used in climate models to make predictions about climate change. These models aid in decision-making for individuals, institutions, communities, and governments.

Physical Science (PS) Core Idea 1: Macroscopic states and characteristic properties of matter depend on the type, arrangement and motion of particles at the molecular and atomic scales. [Structure and Properties of Matter]

PS1.A: Atomic Structure of Matter

Sub-question: *What makes up everything around us?*

All substances are made up of atoms that are in constant motion. These particles are too small to be seen even with a light microscope. Atoms themselves have substructure which determines how they combine, arrange and interact to form all of the substances around us.

Grades K – 2

What kind of parts are objects made of? (macroscopic)

Objects are generally made of different parts. The parts can be made of different materials.

Materials can be natural or manufactured from natural resources.

The identity, characteristics and function of an object depend on the materials/building blocks used to make it, and the way they fit together.

The same materials can exist as a solid or a liquid depending on the temperature. Solids have a definite shape while liquids flow to the lowest level in the container.

Grades 3 – 5

How do the parts of an object affect its structure and function? (macroscopic)

All substances are considered matter. Matter can exist as solid, liquid, or gas. In all forms it can be felt and weighed.

It is possible to break materials apart into pieces too tiny to see. However, the material still exists and continues to have weight even though we can't see it.

You can make a great variety of objects with just a few types of components. The structure, properties and uses of the objects depend on the nature of the components and they ways they attach to one-another, but can be quite different from those of the components.

Knowing about the characteristics of materials helps design uses of them.

Many substances can exist as solid, liquid or gas depending on the temperature. Solids have definite shape and volume, liquids also occupy definite volume, but not shape, gases are made of particles too small to see that move around throughout the full volume of any container.

Grades 6 – 8

How do the building blocks of matter help explain the diversity of materials that exist in the world? (sub-microscopic)

Substances can exist in different states: solid, liquid and gas, depending on the temperature and pressure. Regardless of the state, all matter has mass, and the mass does not change when matter goes from one state to another.

Models of matter consisting of extremely tiny particles that are constantly in motion, with interactions between the particles, can explain states of matter and changes of matter with temperature (in these models particles are non-specific).

The particles that make up matter are so small that they cannot be observed through a light microscope, but can be detected and manipulated by modern tools.

Despite the immense variation and number of substances, all are made from a limited number of types of atoms, called elements. Each type of atom has distinct mass and chemical properties.

The Periodic Table organizes the elements by their mass and chemical properties and provides a useful reference for predicting how they will combine. *(Link to PS1.B)*

Molecules form due to interactions between atoms; molecules range in size from two to hundreds of atoms.

Atoms may interact to form distinct molecules or arrange in extended patterns with no defined endpoint (e.g. crystals, metals).

The chemical composition, the arrangement of atoms, and the way they interact and move determines the state and properties of a substance. The thermal motion of the atoms increases with temperature.

Physical Science (PS) Core Idea 1: Macroscopic states and characteristic properties of matter depend on the type, arrangement and motion of particles at the molecular and atomic scales. [Structure and Properties of Matter]

Grades 6 – 8

Grades 9 – 12

In what ways do the building blocks (atoms) combine to create all of the substances and structures in the universe?

There is a hierarchy of structure within matter. Atoms may interact to form individual molecules or arrange in extended patterns with no defined endpoint. Atoms and molecules combine to form larger, more complex structures, natural or manufactured, with an extensive range of properties. (*link to ET1.A)*

Structures made of atoms and molecules exist over a huge range of scales—from diatomic molecules in a gas to stars.

Substances can exist in different states: solid, liquid, gas or plasma depending on the temperature and pressure. However, many substances are not easily classified into these categories (e.g., gels, colloids).

In a plasma state, a substance is gaseous but a large proportion of the particles are ionized, which affords very different properties than a neutral gas. (e.g., conducts electricity).

Atoms themselves have substructure. The patterns of the periodic table can be related to the patterns of the outermost electrons in the atom, which are those that are involved in chemical bonding. (A few basic types of interactions, or bonds: metal•non-metal (ionic); non-metal•non-metal (covalent); metal•metal (metallic)).

Models of electrical attractions and repulsions involving electrons and atomic nuclei help explain the structure and many properties of substances. *(link to PS2.A)*

Physical Science (PS) Core Idea 1: Macroscopic states and characteristic properties of matter depend on the type, arrangement and motion of particles at the molecular and atomic scales. [Structure and Properties of Matter]

PS1.B: Properties of Matter

Sub-question: *How can you distinguish one substance from another?*

All substances have characteristic measurable properties that depend on the conditions under which they are observed. These properties depend on atomic substructure but do not persist at the atomic level.

Grades K – 2

How can we describe and sort objects?

Objects can be described and sorted based on visual and tactile properties of the materials from which they are made.

When objects are taken apart, their separate parts generally don't have the characteristics of the object.

Materials with different properties can be matched to different uses.

Grades 3 – 5

What characteristics are useful for describing and classifying substances?

Materials can be described and classified by their physical properties such as hardness, flexibility, durability, resistance to water and fire, and ease of conducting heat. Solids can also be classified as metals and non-metals (density is not to be introduced at this level).

Measurements of specific properties provide better ways of telling one substance from another than relying only on what it looks or feels like.

New materials can be made by combining two or more other materials. The new materials have different properties from the original materials.

You cannot make matter but you can refine and process naturally occurring substances to make a great variety of new types of materials with specific useful properties.

Grades 6 – 8

How can we reliably distinguish between substances?

Each pure substance has characteristic physical properties (*density, boiling and melting points, and solubility are appropriate at this level)* and unique chemical properties, which are relatively insensitive to the amount of the sample, so are useful for distinguishing one substance from another.

Measuring the intrinsic properties helps identify and distinguish between different substances. Measuring more precisely, or more different properties, increases confidence of conclusions.

Elements can be grouped as highly reactive metals, less-reactive metals, highly reactive nonmetals and some elements that are non-reactive gases.

Many substances react chemically in characteristic ways with other substances to form new substances with different intrinsic properties. This change in properties results from changes in the way atoms from the original substances combine and arrange.

Grades 9 – 12

What is the source of the properties of a substance?

Using a broader range of properties to characterize substances not only aids in distinguishing between substances, but also provides more information for determining useful applications for them.

The properties for different bulk quantities of a substance are the same. However, as the size of a sample transitions between the bulk material and individual atoms or molecules the intrinsic properties become less reliable, so new, often unexpected, properties that can lead to new functionality are observed.

The four classes of the elements (metals, nonmetals, semimetals, and the noble gases) are defined based on how they interact with other elements, which is related to their electronic structure. (link to PS1.A)

The properties of different substances result from the configurations of atoms in them (e.g. varied types of molecules, crystalline or metallic extended structures)

Chemical properties of elements depend on the atomic substructure, particularly the outermost electron layer. (link to PS1.A)

PS Core Idea 2: Forces due to fundamental interactions underlie all matter structures and transformations; balance or imbalance of forces determines stability and change within all systems. [Interactions, Stability and Change]

PS2.A: Fundamental Interactions

Sub-question: *What are the interactions that help explain phenomena at all scales?*

All known physical phenomena can be explained as due to only a few types of interactions: gravitational, electromagnetic, and, at the nuclear scale, strong and weak interactions. These interactions are the source of forces between particles and particle decays.

Grades K – 2

How can we recognize and distinguish different pulls and pushes?

Objects pull or push each other. Pushes and pulls can have different strengths.

All objects fall down toward the earth because of a pull of the Earth on the object.

Magnets pull/push (attract/repel) other magnets and some materials.

Grades 3 – 5

How can we measure and compare forces?

Pushes and pulls between objects are called forces. Forces can be measured (e.g. using scales and springs) and their values can be compared.

Electrically charged materials can pull or push other material even without touching them.

The magnetic effect of an electric current loop and a bar magnet are similar.

The strength of forces between objects depends on the objects' properties and the distance between them.

Grades 6 – 8

What properties are responsible for different forces?

For any pair of interacting objects, the force exerted by object A on object B is equal in strength to the force that the object B exerts on object A, but in the opposite direction.

The strength of forces between interacting objects decreases as the distance between the objects increases.

Electric and magnetic (electromagnetic) forces can be attractive or repulsive depending on the sign of the charge, direction of current flow and or orientation of a magnet. Their size depends on the magnitude of the charges, currents or magnetic strength involved.

Long-range gravitational interactions govern the evolution and maintenance of structure in the universe. (link to ESS1.B)

Everyday phenomena are generally due to gravitational or electromagnetic interactions.

Gravitational forces between the earth and objects at its surface are large due to the large mass of the Earth, but the gravitational force between two such objects is too small to observe without sensitive instrumentation.

Grades 9 – 12

What kinds of force fields are there and what are their properties?

Forces at a distance are mediated by force fields that can transmit energy through space.

All objects with mass-energy are sources of gravitational fields and are affected by gravitational fields of other such objects.

Magnetic forces and electrical forces are different aspects of a single electromagnetic interaction. All objects with electrical charge or magnetization are sources of electromagnetic fields and can be affected by electromagnetic fields of other such objects.

Newton's law of universal gravitation and Coulomb's law provide the mathematical models to predict the effects of gravitational and electrostatic forces.

Attraction and repulsion of electric charges at the atomic scale explain the structure, properties and transformations of matter. (link to PS1A and B)

Gravitational interactions are negligible effects within matter, except in very large objects (e.g. earth, stars)

The strong and weak interactions are important inside atomic nuclei. These short-range interactions determine nuclear size, stability and radioactive decays. (link to PS2.C and PS4.B)

PS Core Idea 2: Forces due to fundamental interactions underlie all matter structures and transformations; balance or imbalance of forces determines stability and change within all systems. [Interactions, Stability and Change]

PS2.B: Motion and Stability

Sub-question: *How can we predict the continued motion , changes in motion, or stability of an object?*

Unbalanced forces cause change in motion; balanced forces lead to stability.

Grades K – 2

How do you make something move or stay still?
Pushing or pulling on an object can make it move, stop it from moving or change its direction.

Grades 3 – 5

What causes things to move?
A force is a push or a pull. Forces can cause changes in the speed or direction of an object.

The heavier the object the greater force is needed to achieve the same change in motion.

For a given object a larger force causes a larger change in motion.

What happens when you push or pull an object depends not only on what you do, but on all the other things that are pushing or pulling on it, or holding it in place.

Grades 6 – 8

How do we describe and predict motion of objects?
All motion must be described in terms of a reference frame.

To understand how an object will move you have to consider all the forces that are acting upon it.

An unbalanced force will cause a change in the speed and/or direction of an object. If all forces acting on an object are balanced the motion of the object doesn't change.

A static object or system typically has multiple forces acting on or within it, but they are balanced against one another (add to zero net force).

Grades 9 – 12

How can we predict how objects will move?

Newton's law F=ma accurately predicts changes in the motion of a single object due to the forces on it in everyday circumstances, but requires amendment for speed close to the speed of light.

Understanding the forces acting within and on a system allows one to model it and predict how the system will evolve and change.

What happens for any system depends on its starting condition, as well as the forces within it. When the outcome depends very sensitively on the starting condition we call the system chaotic because we cannot measure enough about its starting condition to predict much about its future in detail. For systems of very many particles we can often predict average but not detailed properties and behaviors (e.g., temperature, average motion, average rates of chemical change, but not individual motions or changes of particular molecules).

PS Core Idea 2: Forces due to fundamental interactions underlie all matter structures and transformations; balance or imbalance of forces determines stability and change within all systems. [Interactions, Stability and Change]

PS2.C: Transformations of Matter

Sub-question: *What happens when matter transforms and how do we characterize, explain, and make predictions about the transformations?*

Interactions may induce transformations of matter. When a transformation occurs, some things in a system change while others stay the same. Different factors affect the rate of different transformations. (Transformations here include both physical and chemical changes.)

Grades K – 2

In what way do things around us change? (macroscopic)

Some changes happen quickly. Some changes happen slowly. Changes that happen very fast or very slowly are sometimes hard to see.

Changing temperature can cause a substance to change form but it can still remain the same substance (e.g., melting and refreezing).

Grades 3 – 5

What happens to the parts of a system when the system changes? (macroscale)

When two or more different substances are mixed, often a new substance with quite different characteristics can be formed, especially if the mixture is heated.

Materials seem to appear or disappear in some transformations (e.g., dissolving, evaporation, burning). In the invisible state, the materials still exist but in pieces too small to see. You can detect their presence in various ways.

No matter how the parts are put together to make a product, the weights of the individual parts add up to the weight of the product.

Changing temperature can cause some materials to evaporate or condense.

Conditions and properties of the objects within a system affect how fast or slowly a process occurs (examples include diffusion, rates of reactions).

Collisions between objects change their motion. Sometimes the collision also causes a change in the object.

A system can appear to be unchanging when flows or processes we cannot see are going on in opposite but equal rates.

Systems can change in many patterns over time. A process may move in one direction, shift back and forth, or repeat in cyclical pattern (e.g., day and night or weight on a spring).

Grades 6 – 8

What happens to the building blocks when transformations occur (sub-microscopic)? At this level, only non-nuclear transformations are considered.

When substances undergo transformations (except nuclear), the atoms and molecules that make up the substance may be arranged differently. However, the total number and identity of atoms remains the same.

All transformations involve exchange of energy. The total amount of energy stays the same before, during and after any transformation.

There is a relationship between temperature and kinetic energy of thermal motion. Applying this idea to a particulate model of matter helps explain why temperature changes affect the structure and properties of matter.

Observed patterns of change in a system allow predictions about the future of the system.

Under constant conditions, a system starting out in an unstable state will continue to change until it reaches a stable condition (e.g. hot and cold objects in contact).

Although a system may appear to be unchanging, changes occurring at the molecular level in opposite directions may occur at equal rates.

Physical Science (PS) Core Idea 2 Forces due to fundamental interactions underlie all matter structures and transformations ; balance or imbalance of forces determines stability and change within all systems [Interactions, Stability and Change]

Grades 6 – 8

Grades 9 – 12

What causes transformations to occur and how can we predict the outcome and rates of transformations?

Systems change in predictable ways, understanding what drives the transformations and the cycles within a system help us predict its behavior in a variety of conditions.

Collision theory provides a qualitative model for explaining the condition-dependence of rates of chemical and nuclear processes.

Even processes that release energy can require some collision energy in order to occur because if the reactants or nuclei collide at low relative speed they bounce apart before they get close enough to initiate the reaction.

Matter is stable because interactions within the matter reduce its energy compared to the energy of any pieces it might otherwise fall apart into. It requires addition of energy to take it apart in any way (e.g., to pull off a sticky tape).

The term binding energy is used to describe the size of the energy *reduction* between the separated parts and the stable whole (i.e., the energy needed to take the system apart).

Many of the processes in our daily lives involve chemical transformations in which atoms in a set of colliding molecules get rearranged into a different set of outgoing molecules but the number of atoms of each type is not changed.

At the sub-atomic level chemical processes involve changes in the distribution and motion of electrons, and thus in chemical binding energies. Changes in binding energy are balanced by differences in the kinetic energy of the molecules before and after the collision.

Nuclear processes include fusion and radioactive decays of unstable nuclei (fission, beta and gamma radiation). Nuclear processes involve changes in nuclear binding energies and masses, and release more energy per atom involved than do chemical processes. In these processes atoms change type but the total number of protons plus neutrons does not change.

Total electric charge does not change in any process, but positive and negative charges can be separated starting from charge-neutral material.

PS Core Idea 3: Transfers of energy within and between systems never change the total amount of energy, but energy tends to become more dispersed; energy availability regulates what can occur in any process. [Energy and its Transformations]

PS3.A: Descriptions of Energy

Sub question: *What is energy?*

At the macroscale, energy appears in many different forms. At the atomic scale, all forms of energy can be described in terms of kinetic energy, radiation, and energy that can be released or absorbed due to changes in the state or positions of a system of interacting particles. All forms of energy can be quantified. Energy can be transferred from one system to another and transformed from one form to another, but it cannot be created or destroyed.

Grades K – 2

[Intentionally left blank]

Grades 3 – 5

Why do we call so many different things forms of energy?

Motion is a form of energy. The faster a given object is moving the more of this energy it has.

Motion of one object can be transferred to motion of other objects in a collision.

When moving objects collide, sound and heat are produced.

Electricity can produce motion, sound, heat or light. Electric current can transport energy from place to place through wires. Electricity, sound, heat and light are all forms of energy.

For identical objects at rest, the objects at higher heights have more energy than the objects at lower heights. You can see this because when this energy is converted to motion as the object falls, the higher it started, the faster it hits the floor.

Moving objects, light, and sound carry energy from place to place in an organized fashion.

Energy flows out of hotter regions or objects and into colder ones, cooling the one and heating up the other. This happens in three quite different ways: by contact of solid to solid, carried by flow of fluid in liquid and gas, and by radiant heating which you can feel if you put your hand close to a stove or fire.

Grades 6 – 8

What is energy? (when viewed at the atomic scale)

Motion energy is properly called kinetic energy; it is proportional to the mass of the moving object and grows with the square of its speed.

Thermal energy (the term heat as it is commonly used) includes two quite separate forms of energy; these are thermal motion (motion of atoms or molecules within a substance) and radiation (infrared and light).

When light and other forms of radiation (infrared, ultraviolet) are absorbed by matter their energy generally appears as thermal motion in the matter. In photovoltaic materials it can appear as electrical energy.

Hot objects emit radiation. If they get hot enough we see them glow red and eventually white and then blue.

Temperature is a measure of the average thermal motion in a substance but it is not a measure of quantity of energy. Different amounts of the same substance at the same temperature contain different amounts of thermal energy.

Gravitational potential energy is the energy stored in the interaction of two massive objects, relative to some reference situation.

Energy stored by deformation of an object (e.g. a stretched or compressed spring) is called elastic potential energy.

The terms mechanical energy and chemical energy are not well defined. Mechanical energy generally refers to some combination of motion and potential energy in an operating machine. The term chemical energy generally is used to mean the energy that can be produced by burning fuel or food, or more generally energy released in chemical processes.

PS Core Idea 3: Transfers of energy within and between systems never change the total amount of energy, but energy tends to become more dispersed; energy availability regulates what can occur in any process. [Energy and its Transformations]

Grades 6 – 8

Grades 9 – 12

How do we quantify energy and track its conservation?

All forms of energy can be measured in the same units; historically a variety of different units were introduced for different forms and scales of energy. For bookkeeping energy conservation, we need to know how to convert from one unit system to another, and choose a common one for all forms.

Quantitative application of conservation of energy can predict changes in motion in simple isolated systems (e.g. falling body in a vacuum, colliding pucks on ice). Mathematical expressions for how different forms of potential energy depend on relative particle positions, and for kinetic energy, are needed to do this.

How does energy flow in uncontrolled systems?

Energy tends to dissipate.

The stable configuration of any isolated system is the one that distributes the energy in that system as uniformly as possible between all available forms. Uncontrolled systems always evolve towards more stable states. This principle is useful for understanding stability of structures at every scale from the nucleus to the galaxy, and for predicting the way energy will flow within systems.

Unstable objects are any that can fall apart with no added energy. Eventually they will do so; however, if the energy release in the transition is small, the lifetime for the transition can be very long (e.g. long-lived radioactive isotopes).

PS Core Idea 3: Transfers of energy within and between systems never change the total amount of energy, but energy tends to become more dispersed; energy availability regulates what can occur in any process. [Energy and its Transformations]

PS3.B: **Energy for Life and Practical Use. The Special Role of Food and Fuel.**

Sub question: *If energy is conserved, how can we use it?*

In everyday language we speak of producing, using or wasting energy. This is because energy that is in concentrated form is useful for running machines, generating electricity for heat and light etc, while dissipated energy in the environment is not readily recaptured. Most processes tend to dissipate energy. Food, fuel and electric power can be moved from place to place to provide energy where needed.

Sub question: *How do food and fuel give us energy?*

Food and fuel contain carbohydrates. These substances react with oxygen in burning or in digestive processes to release thermal energy and carbon dioxide and other waste materials. This process is a key energy provider for most animal life and for many forms of electrical generation, transportation and industrial machines.

Grades K – 2

Who needs energy? How do they get it?

Animals need energy to move around and grow. They get it from food.

Plants need energy to grow. They get it from sunlight.

Machines can convert energy from one form to another or can help transfer energy to produce motion, heat, or light.

We need electricity to make heat and light in our homes, and to run small machines etc. We get it from power lines or from batteries.

Grades 3 – 5

What happens when fuel is burned? Where does fuel come from? Where do we get energy? How do we lose it?

Burning fuel is a process that can produce heat, light, and sound. The fuel turns into ashes, smoke and gases.

Burning requires oxygen from the air, and stops when oxygen is not available in the amounts needed (candle in a jar).

Energy cannot be created or destroyed, you have to get it from somewhere, and when you are done with it, it is still around, though not in a useful form.

If energy leaks out of a system, it is usually because the system is heating the surrounding environment.

When we say we "produce energy", we mean we convert some stored energy into the desired form for use – (e.g. water behind a dam flows down and drives a turbine to produce electricity).

For practical purposes it is valuable to be able to transport materials that can be used to produce energy, or transport energy itself, so it is available where and when we need it.

Food and fuel provide energy when they are burned, and are transportable. Batteries are transportable energy storage devices. Electrical energy is distributed via the power grid.

Gasoline and other fossil fuels come out of the ground, but their original source was plants.

PS Core Idea 3: Transfers of energy within and between systems never change the total amount of energy, but energy tends to become more dispersed; energy availability regulates what can occur in any process. [Energy and its Transformations]

Grades 3-5

Grades 6 – 8

What processes produce the energy we use? What process makes things slow down and stop (lose energy)?
Burning fuel and cellular digestion both are chemical transformations. In these processes carbohydrates react with oxygen to produce thermal energy, carbon dioxide and other waste materials.

Energy cannot be made or destroyed. When we talk about processes that produce it, we mean a process to store it in concentrated form or produce electrical energy, or chemical reactions such as burning that release energy.

Plants use sunlight to drive a chemical reaction that needs energy to occur. In this reaction carbon dioxide and water combine to form carbohydrates and release oxygen. (no detailed process at this level).

Carbohydrates in food and carbon-based fuels (coal, oil, gas) are all originally produced by this process.

Moving objects tend to lose energy due to friction with air or surfaces. Friction produces thermal motion. This diffuse energy is generally hard to capture for re-use. Machines are made more efficient by reducing friction on their moving parts.

Grades 9 – 12

Where do we get energy?
Nuclear fusion processes in the center of the sun provide the energy the earth receives as sunlight

Photosynthesis is a complex chemical process that requires both energy input and a catalyst to occur. It is the major way the sun's energy is captured and stored on earth. (see LS1.C)

Electric power generation uses fossil fuels (coal, oil and natural gas), nuclear fission, or renewable resources (solar, wind, tidal, geothermal and hydro-power).

Transportation today chiefly uses fossil fuels but electric and alternate fuel (hydrogen, biofuels) vehicles are a growing sector.

All forms of electrical generation and transportation fuels have associated economic, human, and environmental costs and risks, both short and long term. Technological developments and regulatory decisions can change the balance of these factors. (link to ESS3.C)

What is energy efficiency?
While energy cannot be destroyed, it can be converted to less useful forms, such as noise and thermal energy lost to the surrounding environment. In designing any machine or any system for energy storage and distribution, maximized efficiency means maximized desired impact per input fuel. Efficiency is a major element to optimize because it reduces costs, waste materials and other environmental impacts.

PS Core Idea 3: Transfers of energy within and between systems never change the total amount of energy, but energy tends to become more dispersed; energy availability regulates what can occur in any process. [Energy and its Transformations]

PS3.C Relationship Between Energy and Forces

Sub question*: Forces and energy transfer are both involved in changes of motion, how are they related?*

Forces between two objects indicate that there is energy stored in some interaction between them that can cause the objects to change their motion or change shape. Forces between two interacting objects are always in a direction such that motion in that direction would reduce the energy in the force field between them, however prior motion and other forces affect the actual direction of motion.

Grades K – 2
[Intentionally left blank]

Grades 3 – 5
How does energy get from one object to another?
Forces can transfer energy to or from an object.

Magnets are accompanied by magnetic fields that can exert forces on other magnets and transfer energy from one to the other.

When things collide they can interchange energy by applying forces to each other that change the motions.

Grades 6 – 8
How does energy get from one object to another?
When two objects interact in any way, each applies a force on the other, and these forces can transfer energy between them.

Gravitational interaction between an object and the earth can store energy as the object is raised and release energy as the object falls.

Interactions in matter can store energy in a stretched or compressed spring, which can transfer energy to and from a weight on the spring as the spring changes length.

Magnetic and electric forces between two objects at a distance can transfer energy between the interacting objects.

Grades 9 – 12
What is the relationship between energy interchanges and force fields?
Force fields contain energy and can transmit energy across space from one object to another.

When two objects interacting through a force field change relative position the energy in the force fields and the motion of the objects can be changed.

Forces between two interacting objects are always in a direction such that motion in that direction would reduce the energy in the force field between them, however prior motion and other forces affect the actual direction of motion.

Light and other forms of electromagnetic waves carry energy across space. Light exerts forces on matter and changes the energy of the matter as it is absorbed, reflected or transmitted.

PS Core Idea 4: Our understanding of wave properties, together with appropriate instrumentation, allows us to use waves, particularly electromagnetic and sound waves, to investigate nature on all scales, far beyond our direct sense perception. [Waves as carriers of energy and information]

PS4.A: Wave Properties

***Sub question**: What are the characteristic properties and behaviors of waves?*

Waves carry energy and information from a source to a detector without bulk motion of matter. Waves combine with other waves of the same type to produce complex patterns containing information that can be decoded by detecting and analyzing them.

Grades K – 2

How can you make waves?

Water waves are one of many kinds of waves. Waves are a particular pattern of motion. You can make waves in water by disturbing the surface.

When waves move across the surface of the water in a uniform depth region, the water goes up and down in place, it doesn't move in the direction of the wave (e.g. bobbing cork).

You can make a wave pattern move along a rope by wiggling the end of the rope in a steady rhythm.

Sound makes matter vibrate, and vibrating matter makes sound (e.g. violin string, drum head).

Grades 3 – 5

What happens when two waves meet?

When two waves pass through each other they can add up to a larger motion or cancel one another out (if one is moving up when the other is moving down). However after they cross the original waves emerge just as they were before.

Waves or wave pulses provide a way to send a message (e.g. on a stretched string).

Earthquakes cause seismic waves that are waves in the earth's crust. Motion of the earth surface as these waves pass can do significant damage.

Grades 6 – 8

What features of waves make them good for encoding information?

A simple wave has a repeating pattern with definite wavelength (distance between peaks), and frequency (number of oscillations per second). The intensity (size) of a wave is another important variable.

Combining waves of different frequencies can make a wide variety of patterns and thereby encode information. Such patterns can travel unchanged over long distances, pass through other waves undisturbed, and be detected and decoded far from where they were produced.

Sound is a pressure wave in air. Your ears and brain together are very good at detecting and decoding patterns of information in sound (e.g. speech and music) and distinguishing it from random noise.

For sound waves intensity is related to loudness and frequency to pitch.

When a wave passes an object that is small compared to the wavelength of the wave it is not much affected.

When a wave meets the surface between two different materials or conditions (e.g. sudden change of depth in water, air to water for light) some part of the wave is reflected at the surface and some continues on, but at a different speed. The change of speed between two media can cause a change in the direction of travel of a wave that meets a surface at an angle. This property is used to steer and focus waves in many situations.

A wave can be absorbed (converted to thermal energy) by a medium as it travels through it. The rate of absorption depends on wave frequency and properties of the medium.

Geologists use seismic waves and their reflection at interfaces between layers to probe structures deep in the earth.

Grades 9 – 12

What happens as waves move past each other and as waves interact with objects? *What is resonance?*

Resonance is a phenomenon where a wave builds up in phase in a structure. Structures have particular frequencies for which they resonate. This phenomenon (e.g. waves in a stretched string, vibrating air in a pipe) is used in all musical instruments.

We use the understanding of waves interacting with matter for a wide variety of applications. (see PS4.C)

PS Core Idea 4: Our understanding of wave properties, together with appropriate instrumentation, allows us to use waves, particularly electromagnetic and sound waves, to investigate nature on all scales, far beyond our direct sense perception. [Waves as carriers of energy and information]

PS4.B: Electromagnetic Radiation

Sub question: *What is an electromagnetic wave or electromagnetic radiation?*

Electromagnetic waves are waves of changing electromagnetic fields. They can be detected over a wide range of frequencies of which the visible spectrum of colors detected by our eyes is just a small part.

Grades K – 2

What color is it?

You can only see objects when light is available to light them up.

Some materials allow light to pass through them, some allow only some light through, others block all the light and create a dark shadow on the surface where the light can't reach.

Grades 3 – 5

How does light travel?

The path light travels can be traced as straight lines, except at surfaces between different transparent materials (air and water, air and glass) where the light path gets bent.

Light reflects off solid surfaces. Some surfaces (mirrors) reflect all colors of light; some reflect only a particular range of colors.

You see an object when light reflected from its surface enters your eyes; the color you see depends on the color of available light sources as well as on the properties of the surface.

You can use lenses and prisms to redirect a light beam. Lenses are used in spectacles, telescopes and light microscopes.

Grades 6 – 8

How can we determine and explain properties of light?

Light comes to us from the sun and from distant stars, so it travels through space.

A wave model of light is most useful for explaining color, and the frequency-dependent bending of light at a surface between media.

When light shines on an object it is reflected, absorbed, or transmitted through the object depending on the material of the object and the wavelength (color) of the light.

Grades 9 – 12

What models are useful in describing a broader class of waves that do not need matter to move through space?

Light is an electromagnetic wave. We also call it electromagnetic radiation. Other ranges of wavelengths of electromagnetic waves have other names. (Radio, microwave, infrared, ultraviolet, x-ray, gamma-ray)

Waves are not much disturbed by objects that are small compared to their wavelength so we cannot use visible light to see objects that are small compared to its wavelength, such as individual atoms. All electromagnetic radiation travels through a vacuum at the same speed, which we call the speed of light. Its speed in a medium depends on its wavelength and properties of the medium.

When light or longer wavelength electromagnetic radiation is absorbed in matter it is generally converted into thermal energy. Shorter wavelength electromagnetic radiation (ultraviolet, x-ray, gamma ray) can ionize atoms and cause damage to, or mutations in, living cells.

Atoms of each element emit and absorb characteristic frequencies of light. These spectral lines allow identification of the presence of the element.

Nuclear transitions also have a distinctive gamma-ray wavelength for each transition and can be used to identify and trace radioactive elements.

PS Core Idea 4: Our understanding of wave properties, together with appropriate instrumentation, allows us to use waves, particularly electromagnetic and sound waves, to investigate nature on all scales, far beyond our direct sense perception. [Waves as carriers of energy and information]

PS4.C: Detection and Interpretation, Instrumentation.

***Sub question**: How do we use instruments that transmit and detect light and sound to extend our senses?*

We can use our understanding of electromagnetic radiation, sound and other waves and of their interactions with matter, to design technologies and instruments that greatly extend the range of phenomena we can investigate and have many useful applications.

Grades K – 2

How do we learn about the world around us?

People use their senses to learn about the world around them. Our eyes detect light, our ears detect sound; we can feel vibrations by touch.

Grades 3 – 5

What instruments help us detect and measure things we cannot see directly?

Light from the stars travels a long distance across space, we can detect it with our eyes if the stars are close enough but with a telescope we can see many more stars.

We can use a microscope to see things that are too small to see with our eyes.

We can use sonar (a sound pulse) to measure the depth of the sea, or a laser pulse to measure the distance to the moon because we know how fast light or sound (in water) travels.

Grades 6 – 8

What signals do we use to transmit information? What technology is used to produce, detect and interpret them?

Many signals that we cannot sense directly can be detected by appropriately designed devices (radio, television, cell phone, ultrasound, x-ray).

Instrumentation expands the range of things that science can investigate as well as providing many useful devices.

Medical imaging devices collect and interpret signals from waves that can travel through the body and are affected by structures and motion within it.

Grades 9 – 12

How does instrumentation change over time?

Improved scientific understandings of light and sound and other waves, and their interactions with matter yields increasingly sophisticated technologies. Improved technologies enable new science.

Multiple technologies based on understanding waves and their interactions with matter are part of everyday experience in the modern world (medical imaging, communications, scanners, etc.).

Engineering and Technology (ET) Core Idea 1: The study of the designed world is the study of designed systems, processes, materials and products and of the technologies and the scientific principles by which they function. [The Designed World]

ET1.A: Products, Processes and Systems

Sub-question: *Why were the various products, processes and systems that enable everyday life developed?*

The designed world consists of technological systems designed and created by engineers, technologists, and scientists to meet people's needs and to improve quality of life.

Grades K – 2

What are the products we encounter every day?
We use all kinds of technology everyday. People design products like phones, TVs, computers, machines, and cars, etc., to help us do things.

Everything that people make, from pencils to cities, need be designed and need engineered processes to make them. Designs can change over time, to make things work better.

Grades 3 – 5

How do designers think up new products?
Each product has been designed to serve a function and fulfill a need or a desire of consumers.

Why are new products developed?
In many cases new products replace older products that were designed to perform the same or similar function but were perhaps less efficient or effective.

New products often represent new technologies that allow new solutions for old problems.

New needs and wants occur as society evolves and changes, and new technologies often lead to societal changes (e.g. automobiles instead of horses for transportation).

Grades 6 – 8

How do products and processes interact in technological systems?
New technological processes enable new and improved products. (e.g. improvements in transportation systems make many more foods available in grocery stores).

Why are new products and processes developed?
Products and processes change over time to make systems safer, more efficient and more productive.

Interaction between technology and society drive changes in both, when new societal needs and problems appear there are accompanying new needs for engineered products and processes that address these needs.

Grades 9 – 12

What kinds of processes are used to make various products or provide useful services?
A major focus of engineering is to improve technological processes in order to optimize the products and services that people need or want. Processes vary greatly in different fields of engineering, such as manufacturing, transportation, agriculture, communications, energy, and medical technologies.

What role do technological systems play in changing society?
The evolution of technological systems has influenced the development and advancement of civilization, from the establishment of cities and industrial societies to today's global trade and commerce networks.

Engineering and Technology (ET) Core Idea 1: The study of the designed world is the study of designed systems, processes, materials and products and of the technologies and the scientific principles by which they function. [The Designed World]

ET1.B: Nature of Technology

Sub-question: *What is technology and how does technological development shape our world?*

A technology is a class of designed systems, products, or processes. The designed world is constantly changing as new technologies, tools, and materials are developed.

Grades K – 2

Why do people make things?
People design and make things in order to meet their needs and desires.

Grades 3 – 5

What is technology?
Any method of modification of the natural world done to fulfill human needs or desires is a technology (e.g. irrigation systems, steam-driven engines, electric motors and generators).

How is technology created?
Anyone can modify a technology, invent a new application of technology or make a new product (e.g. invent a new toy, make a dollhouse, or paper airplane) by thinking about what they want to do, gathering the right knowledge and skills, and trying different ways of working until they succeed.

Grades 6 – 8

Why are technologies created?
Technologies include products, processes and systems. Today's technologies include medical and bioengineered devices and treatments as well as those we more traditionally view as the realm of engineers. Engineers develop new technologies to meet individual and societal needs and wants.

Scientific advances may enable new types of technology and new materials for designers to use in developing new products (e.g. steam engines, transistors, lasers).

How do technologies interact with society?
As new technologies become available (e.g. cars, laptop computers and cell phones) they initiate change in society, and create new needs and wants.

The designed world is constantly being changed by this interaction between society and technology.

Grades 9 – 12

What is the difference between inventions and innovations?
Inventions are ideas for entirely new products, processes or systems.

Innovations are ideas for transforming existing technologies so they fulfill a different function or become more widely available.

How does technology advance?
Technology advances through the twin processes of invention and innovation. These processes are supported by the knowledge, creativity, and motivations of individuals in hundreds of different fields, such as engineering, science, business, marketing, economics, law, and environmental protection.

Engineering and Technology (ET) Core Idea 1: The study of the designed world is the study of designed systems, processes, materials and products and of the technologies and the scientific principles by which they function. [The Designed World]

ET1.C: Using Tools and Materials

Sub-question: *How do people use tools and materials to modify or create new technologies?*

A tool is a physical or cyber object that extends people's abilities to design, build, and utilize products, processes, and systems: to cut, shape, or put together materials; to move things from on place to another, or to grow and process food.

Grades K – 2

What is a tool?
A tool is any object that people use to do things better or more easily. Some tools allow us to do things that otherwise could not be done at all.

Which materials are natural and which are made by people?
Some materials (e.g. fabrics and plastics) have been changed from their natural form to meet people's needs or wants, while others occur naturally but may be moved, and shaped for human use (e.g. a rock wall, a wooden chair).

How can different materials be used?
Some materials are better than others for a particular purpose.

Grades 3 – 5

How are tools used to change materials?
A tool is an object that extends people's abilities to change the world: Tools can be used to cut, shape, or put together materials.

Materials can be changed into useful objects by hand-held tools or by machines.

Different kinds of tools are used to measure or modify different materials.

What are other uses of tools?
Tools can be used to move things from one place to another, to grow and process food, to communicate, and to explore space. The term tool can be generalized to any device used to achieve a specific purpose.

Grades 6 – 8

How are tools improved?
Tools have been improved over time to do more difficult tasks and to do tasks more efficiently, accurately, or safely.

How do engineers select materials for a designed product?
Each component of a system has defined criteria for the properties of the material (e.g. conductivity, strength, density) it needs. Considerations of appearance and durability are also significant. Cost and availability also enter into the final choice of material.

How are materials modified to change their properties?
Various processes have been developed to modify materials so they have properties needed for different technologies (e.g. vulcanization of rubber, combining metals into new alloys, and producing fabrics by processes such as weaving, knitting, felting, and dyeing).

Grades 9 – 12

What kinds of tools do scientists and engineers use?
Scientists use tools to observe and measure the natural world, while engineers use tools to design and create technological products. Both use modeling tools to understand complex systems.

How does atomic-scale structure affect the processing of materials?
The atomic-scale structure of a material determines its properties and affects which tools and machines will enable the material to be changed to the desired shape, size, or texture. (link to PS1.B)

Nanotechnology today produces tiny molecular scale structures and materials designed for specific purposes.

ET Core Idea 2: Engineering design is a creative and iterative process for identifying and solving problems in the face of various constraints. [Engineering Design]

ET2.A: Defining and Researching Technological Problems

Sub-question: *How are technological problems defined and researched?*

The first step to solving technological problems is to define the problem in terms of criteria and constraints or limits. It is important to find out how others have solved similar problems and to learn more about the nature of the problem itself.

Grades K – 2

What can people do to solve problems?
People encounter problems and needs every day that can be solved by making something or finding a new way to do something.

Asking questions, making observations, and gathering information are helpful in thinking about how to solve a particular problem or meet a need.

Grades 3 – 5

How can a problem be stated so that it can be solved?
Given a need, want or problem the first step to devising a technological solution is to carefully analyze what is needed and to define a set of criteria for what outcomes are desired and what costs and inputs are feasible in the particular context. Other constraints such as the safety requirements, the environmental impacts and the materials available also need to be defined and listed.

The more clearly a technological problem is stated in this way the easier it is to design and compare possible solutions.

***How have others solved similar problems*?**
When working on a technological problem, it can be helpful to learn how others have solved similar problems.

Grades 6 – 8

What are the criteria for success? What are the constraints*?*
Technological problems can be defined in terms of criteria and constraints or limits.

What scientific principles, laws or theories are relevant?
Since all technologies are constrained by physical laws, it is important to identify the relevant scientific constraints. Other types of constraints are economic, safety, environmental, regulatory and societal.

What kinds of knowledge are needed to solve different technological problems?
Researching technological problems involves the ability to search multiple sources and identify relevant and reliable information.

Engineers also need to develop skill with modeling, using mathematics, and ability to use and adapt special purpose design software.

Grades 9 – 12

How do engineers approach complex problems?
Complicated technological problems can often be broken down into a set of interconnected but simpler problems. This step facilitates a systematic approach.

What are the different ways that problems can be researched?
Researching a technological problem may require several different kinds of research (e.g., scientific experiment, field study, interviews, market research, Internet search, modeling).

ET Core Idea 2: Engineering design is a creative and iterative process for identifying and solving problems in the face of various constraints. [Engineering Design]

ET2.B: Generating and Evaluating Solutions

Sub-question: *How are creative solutions developed and evaluated?*

Finding a solution starts with a creative process that eventually leads to synthesis, focus, and rigorous testing of potential solutions.

Grades K – 2

What are different ways to solve problems?
Often technological problems have more than one solution. Doing things in two different ways is a good way to determine which is the best way to solve a problem.

Grades 3 – 5

How can different solutions be clearly expressed?
Working together and expressing ideas in words, sketches, and models are helpful in coming up with different solutions to technological problems.

How can the best solution be chosen?
After developing several solutions, the best solution can be chosen by comparing each of the solutions with the criteria and constraints developed to define the problem to see which meets them best.

How can different ideas be combined?
Sometimes two or three ideas can be combined into a single idea that is better than any of the individual ideas.

Grades 6 – 8

How can people work together to develop a variety of solutions then mold those ideas into a single workable solution?
Creative solutions are brainstormed and shared, followed by a process of focusing, eliminating, and synthesizing ideas.

How can different solutions be tested and compared?
Systematic methods such as "Pugh Charts" can be used to compare alternative solutions based on criteria and constraints.

Models or prototypes are often used to test solutions and see where they are most likely to fail, to measure their efficiency or productivity and to estimate their cost.

Grades 9 – 12

What scientific knowledge is relevant?
Scientific laws and theories relevant to the problem can be used to suggest solutions, find appropriate materials, and also to help evaluate which approaches are most likely to solve the problem.

What are some ways to find creative solutions?
Creativity occurs in an open-minded problem- oriented environment where multiple ideas and contributions are accepted and examined. Often it helps to have multiple experts each with different disciplinary training and perspective working as a team.

How can computers be used to compare one solution with another?
Computer simulations (i.e., dynamic mathematical models) provide a cost effective way to test how various designs will function over a range of different circumstances and last over time.

ET Core Idea 2: Engineering design is a creative and iterative process for identifying and solving problems in the face of various constraints. [Engineering Design]

ET2.C: Optimizing and Making Tradeoffs

Sub-question: *How can the best possible solution be developed to solve a technological problem?*

Finding the best solution is an iterative process involving decisions concerning tradeoffs among competing criteria, and multiple tests and improvements.

Grades K – 2

What makes one thing better than something else?
Some things that you buy last longer, are more attractive, are less wasteful, work better (faster, easier etc.), or are otherwise more satisfying than others.

Grades 3 – 5

How do design problems differ from mathematics problems?
Most problems in arithmetic have just one solution, although there may be more than one way to reach it. Nearly all design problems have many possible solutions.

Solutions to design problems need to be tested and redesigned several times to arrive at the best available solution.

Grades 6 – 8

How can the best possible design be determined?
Optimizing a solution involves making tradeoffs (i.e., decision to include more of one quality at the expense of another) in order to arrive at the best possible design with respect to a weighting of the various criteria.

A solution that only optimizes one of the criteria is seldom the best all-around solution, although it may be the best in a certain situation or test.

Grades 9 – 12

What are the different factors that must be taken into account when solving technological problems?
Although science and mathematics are important tools that engineers use in finding and testing effectiveness of solutions to a technological problem, the criteria for success are defined in terms of broader considerations in addition to effectiveness. These include cost, safety, reliability, aesthetic, and environmental, social and cultural impacts.

ET Core Idea 3: People are surrounded and supported by technological systems. Effectively using and improving these systems is essential for long-term survival and prosperity. [Technological Systems]

ET3.A: Identifying and modeling technological systems

Sub-question: *What are technological systems and how can they best be modeled and improved?*

Most devices can be broken down into subsystems, and they are also parts of larger systems. Systems also interact with other systems. Systems analysis and modeling are key tools in designing, troubleshooting and maintaining technological systems.

Grades K – 2

What are the parts that make up a whole product?
Almost everything we use is made up of smaller parts that have been put together (e.g. shoes have laces, soles, & tops).

Grades 3 – 5

How can drawings be used to show the way things fit together?
Engineers design products that are made of smaller parts, using sketches or drawings that show how each part relates to every other part in the device.

Each part of a designed system has a specific purpose and a reason why it is included.

When something is not working a first step to fixing it is to analyze what part or subsystem is not functioning as it should.

Grades 6 – 8

How do systems relate to larger and smaller systems?
Most systems can be broken down into subsystems and also are part of larger systems (e.g., cars have subsystems (engine, drivetrain, etc.) and they are also part of the larger transportation system).

How do systems interact with other systems?
The output from one technological system or subsystem (material, energy, or information) can become the input to other systems or subsystems.

Grades 9 – 12

How can designed systems be tested to see how well they meet criteria to solve a problem?
Technological systems are tested and refined using computer simulations and physical and mathematical models to determine how well they meet design criteria and constraints.

ET Core Idea 3: People are surrounded and supported by technological systems. Effectively using and improving these systems is essential for long-term survival and prosperity. [Technological Systems]

ET3.B: Life cycles and maintenance of technological systems

Sub-question: *How can life cycle analysis be utilized to improve technological designs?*

In order to design products with minimal impact on the environment, it's helpful to consider its life cycle, which begins with raw materials, continues through processing, shipment, sales, use, and eventually ends with disposal or recycling.

Grades K – 2

What are things made out of?
Nearly everything that we use is made from materials that have been taken from the land, air, water, or plants and animals.

Grades 3 – 5

Why do things need to be maintained?
Most of the tools, machines, and products we use need to be maintained in order to remain in good working order (e.g. because moving parts get worn and because lubricants get burned up or evaporate).

How can things be fixed if they break down?
If a tool, machine, or product breaks down, troubleshooting can be used to diagnose what needs to be fixed. Often only a small part of the system needs repair or replacement.

Grades 6 – 8

What is life cycle analysis?
Life cycle analysis of a product includes consideration of the resources needed to provide raw materials for the product, the energy needed to create, transport, sell, and use the product, and the waste produced in discarding it.

How does life cycle analysis help designers create better products?
By providing information about the resources needed to create, use, and dispose of products, life cycle analysis can be used by designers to reduce the cost of production and use, make it easier to maintain and repair, and reduce its environmental impact.

Grades 9 – 12

How can complicated systems be kept in working order? Technological systems tend to degrade, so they need maintenance, repair, and upgrading (e.g., engines, painted surfaces, roads and bridges).

Do complex systems always behave as expected?
Complex technological interventions often have risks and side-effects which are not easy to quantify or predict. However it is the responsibility of engineers to try to do so. Risk analysis and risk minimization is an important element in designing any product or technological system.

ET Core Idea 3: People are surrounded and supported by technological systems. Effectively using and improving these systems is essential for long-term survival and prosperity. [Technological Systems]

ET3.C: Control and feedback.

Sub-question: *What are control systems and feedback systems, why are they effective, and how can they be improved?*

Technological systems often include control and feedback components (e.g., house thermostat, alarm systems, stop lights, toilets), which are important for analyzing malfunctions and improving efficiency.

Grades K – 2

What are controls and feedback?
Controls are any part of a system that you can adjust, such as the switch for a light or the brake on a car.

Feedback is when you change what is happening based on noticing something (e.g. noticing you started to trip and taking a quick step to save yourself).

Grades 3 – 5

Why are controls needed?
Controls can be designed to make products easier or safer to use, to regulate conditions (e.g. a thermostat) or to activate a system designed to prevent risks (e.g. sprinkler system in a school triggered by heat or smoke).

Many products have built in components with feedback control systems (e.g. airbag in car triggered by collision).

Grades 6 – 8

How are automatic controls different from manual controls?
Manual controls are those where the user sets and maintains the position of the controller while automatic controls can be set or programmed and then continue to do the job without human intervention, or even can be designed to over-ride human action.

What are feedback and control mechanisms used for?
Feedback systems are those that monitor or measure some property or output of a system and change a control that regulates the system based on the result of the measurement (e.g. thermostat).

Feedback and control systems are important to keep complex systems functioning smoothly with little active intervention.

Grades 9 – 12

How are control systems constructed?
Most modern control systems include both digital and mechanical sub-components. Like any technological system they are designed, usually they are designed as a subsystem during the design of the system that they regulate.

ET Core Idea 4: In today's modern world everyone makes technological decisions that affect or are affected by technology on a daily basis. Consequently, it is essential for all citizens to understand the risks and responsibilities that accompany such decisions. [Technology and Society]

ET4.A: Interactions of technology and society

Sub-question: *What are the societal risks and benefits of technologies?*

The development of new technologies is driven by the needs of society and often provides new benefits; but new technologies may also introduce risks and may change social norms.

Grades K – 2

How has technology changed the way people live?
Technology touches every aspect of your life, the place where you live, the materials in your home and in your clothes, the way you travel from one place to another, how your food is produced and brought to the nearby stores, the entertainment you enjoy.

One way to see how you depend on technology is to see what happens in a power failure or when the car has no gas.

Grades 3 – 5

What are some possible problems of new technologies?
Technologies are created to serve needs and wants of people, but using them also involves risks.

Why do technologies change?
Because people's needs and wants change, new technologies are developed and old ones are improved to meet those changes. New technologies often change aspects of society and create new needs and wants.

Grades 6 – 8

Why do technologies vary from one locale to another?
Cultural beliefs and practices and social norms affect people's decisions about technology. Consequently, technologies vary from country to country and even by region within countries (e.g. a simple efficient stove may work well for one style of cooking but not for another).

Grades 9 – 12

How do new technologies arise and what problems might they cause?
New technologies introduce new benefits and new risks and undesired impacts, and the trade-offs between these must be considered by the designers, and by society, which regulates their use, and by individuals, who make personal choices about using them.

Scientists and engineers have a special responsibility to inform society if they discover any new risk or side-effect associated with a particular product or process.

ET Core Idea 4: In today's modern world everyone makes technological decisions that affect or are affected by technology on a daily basis. Consequently, it is essential for all citizens to understand the risks and responsibilities that accompany such decisions. [Technology and Society]

ET4.B: Interactions of technology and environment

Sub-question: *How have the development and uses of technologies brought about changes in the natural environment?*

Some technological decisions involve tradeoffs between environmental and economic needs, while others may have positive effects for both the economy and the environment.

Grades K – 2

How do technologies affect the world around us?

The use of technology can affect the environment, including land, air, water, or plants and animals.

Grades 3 – 5

How might the environment be affected when making tradeoffs during the design of new technologies?

Some technological decisions involve tradeoffs between environmental and economic needs, while others may have positive effects for both the economy and the environment.

Grades 6 – 8

Why do technologies vary from one locale to another?

Cultural beliefs and practices and social norms affect people's decisions about technology. Consequently, technologies vary from country to country and even by region within countries (e.g. a simple efficient stove may work well for one style of cooking but not for another).

Grades 9 – 12

How can computers reduce the environmental impact of new technologies?

Computer simulations and models are used to analyze the complex interaction between natural and human-made systems (e.g., environmental systems monitoring).

What are unanticipated consequences?

However, no matter how carefully new technologies are developed they may have unanticipated environmental consequences.

ET Core Idea 4: In today's modern world everyone makes technological decisions that affect or are affected by technology on a daily basis. Consequently, it is essential for all citizens to understand the risks and responsibilities that accompany such decisions. [Technology and Society]

ET4.C: Analyzing issues involving technology and society

Sub-question: *How can citizens analyze issues about technology and society?*

Technological decisions can be analyzed for intended and unintended consequences to adjust designs for maximum benefit or minimum negative impact.

Grades K – 2

How can some technologies that could cause harm?

Examples from daily life illustrate that a given technology can be very helpful if used responsibly, but dangerous if used without regard to consequences.

Grades 3 – 5

How can people determine if a technology they are using may be harmful to others?

People are responsible for thinking about what may happen when they use technologies that may harm other people. That means learning as much as possible about the effects of different technologies, and being open to information from others.

Grades 6 – 8

What should be taken into account when considering a possible technological decision?

Technological decisions can be analyzed for intended and unintended consequences.

Some designs can be adjusted to achieve maximum benefit with minimum negative impact.

Grades 9 – 12

What are the responsibilities of people who create technologies; and those who use them?

Engineers, scientists, and others who create the designed world are responsible for preventing harm to the people who use the products, processes, and systems they design, while users of new technologies can make conscious decisions to reduce negative impacts on individuals, society or the environment.

Appendix A

Biographical Sketches of Committee Members

Helen R. Quinn *(Chair)* is Professor Emerita of Physics at SLAC National Accelerator Laboratory. Dr. Quinn is a theoretical physicist who was inducted into the National Academies in 2003. She served as the president of the American Physical Society in 2004. In addition to her scholarship in physics, Dr. Quinn has had a long term involvement in science education and in the continuing education of science teachers. She was an active contributor to the California State Science Standards development process. She is a former president and founder of the non-profit Contemporary Physics Education Project. She served as chair of the Review and Evaluation of NASA's Pre-College Education Program Committee. She has been a member of the Committee on Science Learning, K-8; the Federal Coordinating Committee on Science, Mathematics and Technology Education, as well as, the Center for Education Advisory Board. She received a Ph.D. in physics from Stanford University in 1967.

Wyatt W. Anderson is the Alumni Foundation Distinguished Professor in the genetics department at the University of Georgia. He is also a member of the National Academy of Sciences. His research interests include evolutionary genetics of mating behavior and chromosomal polymorphisms of Drosophila species; evolutionary genomics of Drosophila; science education and minority participation in college science curricula. He has served on a number of NRC committees, including Section 27: Evolutionary Biology, Committee to Review Northeast Fishery Stock Assessments, and Committee on the Release of Genetically Engineered Organisms into the Environment. He earned his B.S. in Molecular Evolution and his M.S. in

Pop. Genetics and Pop. Biology from the University of Georgia. He earned his Ph.D. in Science Literacy and Education from the Rockefeller University.

Tanya Atwater is a Professor of Tectonics at the University of California, Santa Barbara. Dr. Atwater's research has concerned various aspects of tectonics, ranging from the fine details of sea floor spreading processes to global aspects of plate tectonics. She has participated in or led numerous oceanographic expeditions in the Pacific and Atlantic Oceans, including twelve dives to the deep sea floor in the tiny submersible, Alvin. She is especially well known for her works on the plate tectonic history of western North America, in general, and of the San Andreas fault system, in particular, work that is presently taking her in exciting new directions. Dr. Atwater is devoted to science communication, teaching students at all levels in the University, presenting numerous workshops and field trips for K-12 teachers, consulting for the written media, museums, TV and video producers, etc. Dr. Atwater serves on various national and international committees and panels. She is a fellow of the American Geophysical Union and the Geological Society of America and was a co-winner of the Newcomb Cleveland Prize of the American Association for the Advancement of Science and was elected to the National Academy of Sciences in 1997. She received her education at the Massachusetts Institute of Technology, the University of California at Berkeley, and Scripps Institute of Oceanography, completing her PhD in 1972.

Philip Bell pursues a cognitive and cultural program of research across diverse environments focused on how people learn in ways that are personally consequential to them. He is an associate professor of the Learning Sciences at the University of Washington and the Geda and

Phil Condit Professor of Science and Mathematics Education. He directs the ethnographic and design-based research of the Everyday Science and Technology Group as well as the University of Washington Institute for Science and Mathematics Education that cultivates innovative projects in P-20 STEM education between university groups and community partners. Dr. Bell has studied everyday expertise and cognition in science and health, the design and use of emerging learning technologies in science classrooms, children's argumentation and conceptual change in science, culturally responsive science instruction, the use of emerging digital technologies within youth culture, and new approaches to inquiry instruction in science. He is a Co-Lead of the Learning in Informal and Formal Environments (LIFE) Science of Learning Center (http://life-slc.org/) and is a Co-PI of COSEE-Ocean Learning Communities (http://cosee-olc.org/). Dr. Bell is a member of the NRC's Board on Science Education, and he co-chaired the recent consensus committee on Learning Science in Informal Environments. He has a background in human cognition and development, science education, computer science, and electrical engineering. He earned his Ph.D. in Education in Human Cognition and Development from the University of California, Berkeley.

Thomas B. Corcoran is Co-Director of Consortium for Policy Research and Education (CPRE) at Teachers College, Columbia University. He has been a state policymaker, a designer of programs to improve teaching, a researcher, an evaluator, and an advisor to governors, state legislatures, foundations, and reform organizations. His research interests focus on the linkages between research and practice, the use of evidence-based instructional practices, design of knowledge transfer systems for public education, the effectiveness of professional development, and the impact of changes in work environments on the productivity of teachers and students. He heads the Center on Continuous Instructional Improvement, funded by the Hewlett Foundation and Teachers College projects in Jordan and Thailand. He also has served on the NRC K-8 Science Study Committee. He is the author of several books and numerous papers, articles, and book chapters. Since 1998 he has taught policy analysis at the Woodrow Wilson School of International and Public Affairs at Princeton University. Mr. Corcoran earned an M.Ed. from the University of London.

Rodolfo Dirzo is a Professor of Biology at Stanford University. Dr. Dirzo is one of the world's leading tropical forest ecologists and conservation biologists. He has performed seminal work on the evolutionary ecology. He carried out classical experimental studies on the ecosystem significance of biodiversity loss, fragmentation, and deforestation. He is a foreign associate of the National Academy of Science. He is also a member of The Mexican Academy of Sciences and of The California Academy of Sciences. Dr. Dirzo has been awarded the Presidential Award in Ecology, Secretary of Environment, Mexico. He was a Pew Scholar in Conservation, The Pew Charitable Trust; and the Outstanding Service Award: Teaching, Organization for Tropical Studies. He earned his M.Sc. and his Ph.D. from the University of Wales UK.

Phillip A. Griffiths is Director Emeritus and Professor of Mathematics at the Institute for Advanced Study (IAS), which he led from 1991 to 2003. He was formerly provost and James B. Duke Professor of Mathematics at Duke University and professor of mathematics at Harvard. Over the last four decades, Phillip Griffiths has been a central figure in mathematics. He has made crucial contributions in several fields, including complex analysis, algebraic geometry, and differential systems. Dr. Griffiths chaired the committee that produced the Carnegie Corporation report "The Opportunity Equation." Dr. Griffiths served on the National Science Board from 1991-1996. He is a member of the National Academy of Sciences and a Foreign Associate of the Third World Academy of Sciences. Dr. Griffiths has served as a member, ex-officio member, and chair for numerous NRC committees, including the Mathematical Sciences Education Board; Committee on Science, Engineering and Public Policy; Center for Science, Mathematics and Engineering Education Advisory Board; and the U.S. National Committee for Mathematics. He is currently a member of the NRC Board on African Science Academy Development. He received his M.S. in mathematics from Wake Forest University and his Ph.D. in mathematics from Princeton University.

Dudley R. Herschbach is an Emeritus Professor in the Department of Chemistry and Chemical Biology at Harvard University and a Professor of Physics at Texas A & M University during the fall term. He won the 1986 Nobel Prize in Chemistry jointly with Yuan T. Lee and John C. Polanyi for their contributions concerning the dynamics of chemical elementary processes. Dr. Herschbach has been a strong proponent of science education and science among the general public, and frequently gives lectures to students of all ages, imbuing them with his infectious enthusiasm for science and his playful spirit of discovery. He is engaged in several efforts to improve K-12 science education and public understanding of science. He is a board member of the Center for Arms Control and Non-Proliferation and is the chairman of the board for Society for Science & the Public. Dr. Herschbach is a member of the National Academy of Sciences. He has served on the NRC Committee on Education and Employment of Women in Science and Engineering; the Panel for National Science Education Standards and Television Project; and the Board of Overseers and the Communications Advisory Committee. Dr. Herschbach received a

B.S. in mathematics and an M.S. in chemistry from Stanford University. He earned an A.M. in physics and a Ph.D. in chemical physics from Harvard University.

Linda P.B. Katehi is Chancellor of the University of California, Davis. Previously, she served as provost and vice chancellor for academic affairs at the University of Illinois at Urbana-Champaign; the John Edwardson Dean of Engineering and professor of electrical and computer engineering at Purdue University; and associate dean for academic affairs and graduate education in the College of Engineering and professor of electrical engineering and computer science at the University of Michigan. Professor Katehi led the effort to establish the Purdue School of Engineering Education, the first department at a U.S. university focused explicitly on engineering education, particularly on K–12 engineering curricula, standards, and teacher education. The author or coauthor of 10 book chapters, she has published more than 600 articles in refereed journals and symposia proceedings and owns 16 patents. She is a member of the National Academy of Engineering (NAE), a fellow and board member of the American Association for the Advancement of Science, chair of the Nominations Committees for the National Medal of Science and National Medal of Technology and Innovation, and a member of the Kauffman National Panel for Entrepreneurship. She is currently a member of a number of NAE/National Academy of Sciences committees and the Advisory Committee for Harvard Radcliffe College and a member of the Engineering Advisory Committees for Caltech, the University of Washington, and the University of California, Los Angeles.

John C. Mather is a Senior Astrophysicist at the U.S. space agency's (NASA) Goddard Space Flight Center in Maryland and adjunct professor of physics at the University of Maryland, College Park. Dr. Mather won the Nobel Prize in Physics for his work on the Cosmic

Background Explorer Satellite (COBE) with George Smoot. COBE was the first experiment to precisely measure the black body form and anisotropy of the cosmic microwave background radiation, helping to cement the Big Bang theory of the universe. In 2007, Dr. Mather was listed among Time magazine's 100 Most Influential People in The World. Dr. Mather is also the senior project scientist for the James Webb Space Telescope, a space telescope to be launched to the Sun-Earth Lagrange point L2 in 2014. He was a member of the NRC Board on Physics and Astronomy; he served on the Committee on Physics of the Universe. He earned his B.A. in Physics from Swarthmore College and his Ph.D. in Physics from the University of California, Berkeley.

Brett D. Moulding is Director of the Utah Partnership for Effective Science Teaching and Learning, a five district professional development collaborative. He was the director of curriculum and instruction at the Utah State Office of Education before retiring in January of 2008. He was the state science education specialist and coordinator of curriculum from 1993 to 2004. He taught chemistry for 20 years at Roy High School in the Weber school district and served as the district science teacher leader for eight years. Moulding received the Governor's Teacher Recognition Award, the Presidential Award for Excellence in Mathematics and Science Teaching and the Award of Excellence in Government Service from the Governor's Science and Technology Commission. He served on the Triangle Coalitional Board, the NAEP 2009 Framework Planning Committee and was the president of the Council of State Science Supervisors from 2003 - 2006. He received his Administrative Supervisory Certificate from Utah State University. Mr. Moulding earned a B.S. in chemistry from the University of Utah, Salt Lake City, and a M.Ed. from Weber State University, Ogden, UT.

Jonathan Osborne holds the Shriram Family Professorship in Science Education at Stanford University. Prior to joining Stanford, he was a professor of science education at King's College, University of London. His research focus is a mix of work on policy and pedagogy in the teaching and learning of science. In the policy domain, he is interested in exploring students' attitudes toward science and how school science can be made more worthwhile and engaging, particularly for those who will not continue with the study of science. In pedagogy, the focus has been on making the case for the role of argumentation in science education both as a means of improving the use of a more dialogic approach to teaching science and improving student understanding of the nature of scientific inquiry. He led the project on 'Enhancing the Quality of Argument in School Science Education,' from which IDEAS (Ideas, Evidence and Argument in Science Education) materials to support teacher professional learning were developed. Dr. Osborne was one of the partners in the NSF funded Centre for Informal Learning and Schools. He earned his Ph.D. in education from King's College, University of London.

James W. Pellegrino is Liberal Arts and Sciences Distinguished Professor and Distinguished Professor of Education at the University of Illinois at Chicago (UIC). He is co-director of UIC's interdisciplinary Learning Sciences Research Institute. Dr. Pellegrino's current work is focused on analyses of complex learning and instructional environments, including those incorporating powerful information technology tools, with the goal of better understanding the nature of student learning and the conditions that enhance deep understanding. A special concern of his research is the incorporation of effective formative assessment practices, assisted by technology, to maximize student learning and understanding. Dr. Pellegrino has served on the NRC Board on

Testing and Assessment and co-chaired the Committee on the Cognitive Science Foundations for Assessment, which issued the report Knowing What Students Know: The Science and Design of Educational Assessment. He recently helped the College Board build new frameworks for curriculum, instruction, assessment and professional development in AP Biology, Chemistry, Physics, and Environmental Science. Dr. Pellegrino earned his B.A. in psychology from Colgate University, Hamilton, New York and both his M.A. and Ph.D. from the University of Colorado.

Stephen L. Pruitt is the Chief of Staff for the Office of the State Superintendent of Schools in the Georgia Department of Education. Mr. Pruitt is the current president of the Council of State Science Supervisors. Before joining Georgia's Department of Education he taught high school science for 12 years. Mr. Pruitt supervised the revision and implementation of Georgia's new science curriculum. The Georgia Performance Standards have taken Georgia in a new direction in education with an emphasis in conceptual learning and inquiry. He has served in the position of Director of the Division of Academic Standards where he supervised the implementation of all content areas' new curriculum. He now serves as the Chief of Staff for Assessment and Accountability where he supervises the development and operation of all state testing and Adequate Yearly Progress determinations. Mr. Pruitt received a B.S. in Chemistry from North Georgia College; and an M.Ed. from State University of West Georgia. He is currently completing a Ph.D. in chemistry education from Auburn University.

Brian Reiser (Ph.D. 1983, Cognitive Science, Yale) is Professor of Learning Sciences in the School of Education and Social Policy at Northwestern University. Reiser's research examines how to make scientific practices such as argumentation, explanation, and modeling meaningful and effective for classroom teachers and students. This design research investigates the cognitive and social interaction elements of learning environments supporting scientific practices, and design principles for technology-infused curricula that embed science learning in investigations of contextualized data-rich problems. Reiser leads the MoDeLS project (Modeling Designs for Learning Science), to develop an empirically-based learning progression for the practice of scientific modeling, and BGuILE (Biology Guided Inquiry Learning Environments), developing software tools for supporting students in analyzing biological data and constructing explanations. Reiser is also on the leadership team for IQWST (Investigating and Questioning our World through Science and Technology), a collaboration with the University of Michigan developing a middle school project-based science curriculum. Professor Reiser was a founding member of the first graduate program in Learning Sciences, created at Northwestern, and chaired the program from 1993, shortly after its inception, until 2001. He was co-principal investigator in the NSF Center for Curriculum Materials in Science, exploring the design and enactment of science curriculum materials, and served on the NRC panel authoring the report Taking Science to School, and the editorial boards of Science Education and The Journal of the Learning Sciences.

Rebecca R. Richards-Kortum is the Stanley C. Moore Professor of Bioengineering at Rice University. Dr. Richards-Kortum is also a member of the National Academy of Engineering. Her work has focused on translating research that integrates advances in nanotechnology and molecular imaging with microfabrication technologies to develop optical imaging systems that are inexpensive, portable, and provide point-of-care diagnosis. This basic and translational research is highly collaborative and has led to new technologies to improve the early detection of cancers and other diseases, especially in impoverished settings. Over the past few years, Dr.

Richards-Kortum and collaborators have translated these technologies from North America to both low- and medium-resource developing countries (Botswana, India, Taiwan, Mexico, and Brazil). Dr. Richards-Kortum has received numerous awards for her reseach and teaching, including: Presidential Young Investigator (1991) and Presidential Faculty Fellow (1992) awards from the National Science Foundation; the Becton Dickinson Career Achievement Award from the Association for the Advancement of Medical Instrumentation (1992); the Chester F. Carlson Award (2007) from the American Society for Engineering Education. She served on the inaugural National Advisory Council for Biomedical Imaging and Bioengineering for the National Institutes of Health (2002-2007), was elected fellow of the American Association for the Advancement of Science and Biomedical Engineering Society (2008). She served on the NRC Committee on Being a Scientist: Responsible Conduct in Research, 3rd Edition. She holds a Ph.D. in Medical Physics and an M.S. in Physics from Massachusetts Institute of Technology.

Walter G. Secada is the Senior Associate Dean of the School of Education and the Chair of the Department of Teaching and Learning at the University of Miami. Prior to moving to UM, Dr. Secada was professor of curriculum and instruction at the University of Wisconsin—Madison and the director of Diversity in Mathematics Education. Dr. Secada's research interests have included equity in education, mathematics education, bilingual education, school restructuring, professional development of teachers, student engagement, and reform. Dr. Secada has been associate director and Co-PI of Promoting Science among English Language Learners (P-SELL) with a High-Stakes Testing Environment, associate director and Co-PI of Science Made Sensible; and a member of the University's Social Sciences Institutional Review Board at UM. Dr. Secada has worked on the development of a secondary-school mathematics and science academy at UM. As director of the U.S. Department of Education's Hispanic Dropout Project, he was senior author of its final report, No More Excuses. He earned a BA in philosophy from the University of Notre Dame, an M.S. in mathematics and Ph.D. in education, both from Northwestern University.

Deborah C. Smith is an Assistant Professor in the Department of Curriculum and Instruction at Pennsylvania State University. Dr. Smith teaches elementary science methods, and graduate courses in science curriculum, the history, philosophy, and sociology of science, and science teacher knowledge. She is a former preschool and elementary school teacher, with a background in biology. Her research focuses on how teachers and young children build communities of scientific discourses and practices in the early years of schooling. As part of her research on elementary teachers' scientific knowledge and teaching practices in professional development, she has also co-taught with elementary teachers in Delaware, Michigan, and Pennsylvania. She was the author and co-PI on a five-year National Science Foundation grant to Lansing (MI) School District and Michigan State University, in which grade level groups of K-8 teachers studied scientific content, standards-based and inquiry-oriented curriculum design, research-based teaching practices, and their students' science learning. She served on the National Research Council's (NRC) Teacher Advisory Committee, and was a consultant for the NRC's popular publication, Ready, Set, Science! She currently serves on the NRC's Committee on conceptualizing a new framework for K-12 science standards. Dr. Smith earned her B.S. in biology from Boston University, M.A.T. in science education from the Harvard Graduate School of Education, and her Ph.D. in curriculum and instruction from the University of Delaware.

Appendix B

Design Teams

Earth and Space Science

Michael Wysession *(Lead)*, Department of Earth and Planetary Sciences, Washington University in Saint Louis

Scott Linneman, Geology Department, Western Washington University

Eric Pyle, Department of Geology & Environmental Science, James Madison University

Dennis Schatz, Pacific Science Center

Don Duggan-Haas, Paleontological Research Institution and its Museum of the Earth

Life Science

Rodger Bybee *(Lead)*, BSCS

Bruce Fuchs, National Institutes of Health

Kathy Comfort, WestEd

Danine Ezell, San Diego County Office of Education

Physical Science

Joseph Krajcik *(Lead)*, School of Education, University of Michigan

Shawn Stevens, School of Education, University of Michigan

Sophia Gershman, Princeton Plasma Physics Lab & Watchung Hills Regional High School

Arthur Eisenkraft, Graduate College of Education, University of Massachusetts

Angelica Stacy, Department of Chemistry, University of California, Berkeley

Engineering and Technology

Cary Sneider *(Lead)*, Center for Education, Portland State University

Rodney L. Custer, Department of Technology, Illinois State University

Jacob Foster, Massachusetts Department of Elementary and Secondary Education

Yvonne Spicer, National Center for Technological Literacy, Museum of Science, Boston

Maurice Frazier, Chesapeake Public School System