Appendix VIII

Value of Crosscutting Concepts and Nature of Science in Curricula

Crosscutting Concepts in Curricula

Crosscutting concepts are overarching themes that emerge across all science and engineering disciplines. These themes provide the context for disciplinary core ideas and enable students to "develop a cumulative, coherent, and usable understanding of science and engineering" (NRC, 2012, p. 4-1). Thus, crosscutting concepts bridge engineering, physical, life, and Earth/space sciences, and offer increased opportunities for organizing science and technology/engineering curricula across disciplines. The *Framework for K–12 Science Education* (NRC, 2012) defines crosscutting concepts as "concepts that bridge disciplinary boundaries, having explanatory value throughout much of science and engineering" (p. 83).

The NRC *Framework* identifies nine crosscutting concepts that bridge disciplines, uniting core ideas across STE. These concepts are intended to help students deepen their understanding of the disciplinary core ideas, and develop a coherent and scientifically based view of the world. They are:

1. **Patterns.** Observed patterns of forms and events guide organization and classification, and they prompt questions about relationships and the factors that influence them.
2. **Cause and Effect: Mechanism and Explanation.** Events have causes, sometimes simple, sometimes multifaceted. A major activity of science and engineering is investigating and explaining causal relationships and the mechanisms by which they are mediated. Such mechanisms can then be tested across given contexts and used to predict and explain events in new contexts or design solutions.
3. **Scale, Proportion, and Quantity.** In considering phenomena or design solutions, it is critical to recognize what is relevant at different measures of size, time, and energy and to recognize how changes in scale, proportion, or quantity affect a system's structure or performance.
4. **Systems and System Models.** Defining the system under study—specifying its boundaries and making explicit a model of that system—provides tools for understanding and testing ideas that are applicable throughout science and engineering.
5. **Energy and Matter: Flows, Cycles, and Conservation.** Tracking fluxes of energy and matter into, out of, and within systems, helps one understand the systems' possibilities and limitations.
6. **Structure and Function.** The way in which an object or living thing is shaped and its substructure determine many of its properties and functions.
7. **Stability and Change.** For natural and built systems alike, conditions of stability and determinants of rates of change or evolution of a system are critical elements of study.

8. **Interdependence of Science, Engineering, and Technology.** Scientific inquiry, engineering design, and technological development are interdependent.
9. **Influence of Engineering, Technology, and Science on Society and the Natural World.** Scientific and technological advances can have a profound effect on society and the environment.

The NRC *Framework* notes that crosscutting concepts have been featured prominently in other science documents about what all students should learn for the past two decades. They have been called "common themes" in *Science for All Americans* (AAAS, 1989) and *Benchmarks for Science Literacy* (AAAS, 1993), and "unifying concepts and processes" in *National Science Education Standards* (NRC, 1996). Although these ideas have been consistently included in previous standards documents, the NRC *Framework* recognizes that "students have often been expected to build such knowledge without any explicit instructional support" (NRC, 2012, p. 83). Crosscutting concepts can help students think of science learning not as memorization of isolated or disconnected facts, but as integrated and interrelated concepts. This is a fundamental understanding of STE that requires explicit instruction to help all students make connections among big ideas that cut across disciplines.

Principles for Integrating Crosscutting Concepts in Curricula

The NRC *Framework* recommends embedding crosscutting concepts in the STE curriculum beginning in the earliest years of schooling and suggests a number of principles for how they can be used:

- **Use crosscutting concepts in curricula and instruction to help students better understand core ideas in STE.** When students encounter new phenomena or design problems—whether in a science lab, field trip, or on their own—they need mental tools to help engage in and come to understand the phenomena from a scientific and technological point of view. Familiarity with crosscutting concepts can provide that perspective. For example, when approaching a complex phenomenon (either a natural phenomenon or a mechanical system), it makes sense to begin by observing and characterizing the phenomenon in terms of patterns. A next step might be to simplify the phenomenon by thinking of it as a system and modeling its components and how they interact. In some cases it would be useful to study how energy and matter flow through the system, or to study how structure affects function (or malfunction). These preliminary studies may suggest explanations for the phenomena; these could be checked by predicting patterns that might emerge if the explanation is correct, then matching those patterns with those observed in the real world.
- **Use crosscutting concepts in curricula and instruction to help students better understand science and engineering practices.** Because these concepts address fundamental aspects of the world, they also inform the way humans attempt to understand it. Different crosscutting concepts align with different practices; when students carry out these practices, they are often addressing one of these crosscutting concepts. For example, when students analyze and interpret mathematical or visual data, they are often looking for patterns in observations. The practice of planning and carrying out an investigation is often aimed at identifying cause and effect relationships: If you poke or prod something, what will happen? The crosscutting concept of "Systems and System Models" is clearly related to the practice of developing and using models.
- **Repeat crosscutting concepts in different contexts to build familiarity.** While repetition is not a feature of the standards themselves, repeating crosscutting concepts within and across pre-K−12 helps them "become common and familiar touchstones across the disciplines and grade levels" (NRC, 2012, p. 83).

- **Crosscutting concepts should grow in complexity and sophistication across the grades.** As students grow in their understanding of the science disciplines, curricula should reflect an increasing depth of crosscutting concepts as well. The charts below (from the NGSS) describe increasingly sophisticated understandings of the crosscutting concepts across grade spans that can or should be integrated into curricula and instruction.

Progression of Crosscutting Concepts Across the Grades

Following is a brief summary of how each crosscutting concept increases in complexity and sophistication across the grades. See the NRC *Framework* for a detailed description of the substance and particulars of each.

1. Patterns

Progression Across the Grades
In grades pre-K–2, students can recognize that patterns in the natural and human-designed world can be observed, used to describe phenomena, and used as evidence.
In grades 3–5, students can identify similarities and differences in order to sort and classify natural objects and designed products. They identify patterns related to time, including simple rates of change and cycles, and use these patterns to make predictions.
In grades 6–8, students can recognize that macroscopic patterns are related to the nature of microscopic and atomic-level structure. They identify patterns in rates of change and other numerical relationships that provide information about natural and human designed systems. They use patterns to identify cause and effect relationships and use graphs and charts to identify patterns in data.
In grades 9–12, students can observe patterns in systems at different scales and cite patterns as empirical evidence for causality in supporting their explanations of phenomena. They recognize that classifications or explanations used at one scale may not be useful or need revision using a different scale, thus requiring improved investigations and experiments. They use mathematical representations to identify certain patterns and analyze patterns of performance in order to re-engineer and improve a designed system.

2. Cause and Effect: Mechanism and Explanation

Progression Across the Grades
In grades pre-K–2, students can learn that events have causes that generate observable patterns. They design simple tests to gather evidence to support or refute their own ideas about causes.
In grades 3–5, students can routinely identify and test causal relationships and use these relationships to explain change. They understand events that occur together with regularity might or might not signify a cause and effect relationship.
In grades 6–8, students can classify relationships as causal or correlational and recognize that correlation does not necessarily imply causation. They use cause and effect relationships to predict phenomena in natural or designed systems. They also understand that phenomena may have more than one cause, and some cause and effect relationships in systems can only be described using probability.
In grades 9–12, students can understand that empirical evidence is required to differentiate between cause and correlation and to make claims about specific causes and effects. They suggest cause and effect relationships to explain and predict behaviors in complex natural and designed systems. They also propose causal relationships by examining what is known about smaller-scale mechanisms within the system. They recognize that changes in systems may have various causes that may not have equal effects.

3. Scale, Proportion and Quantity

Progression Across the Grades
In grades pre-K–2, students can use relative scales (e.g., bigger and smaller, hotter and colder, faster and slower) to describe objects. They use standard units to measure length.
In grades 3–5, students can recognize that natural objects and observable phenomena exist from the very small to the immensely large. They use standard units to measure and describe physical quantities such as weight, time, temperature, and volume.
In grades 6–8, students can observe time, space, and energy phenomena at various scales, using models to study systems that are too large or too small. They understand phenomena observed at one scale may not be observable at another scale, and the function of natural and designed systems may change with scale. They use proportional relationships (e.g., speed as the ratio of distance traveled to time taken) to gather information about the magnitude of properties and processes. They represent scientific relationships through the use of algebraic expressions and equations.
In grades 9–12, students can understand that the significance of a phenomenon is dependent on the scale, proportion, and quantity at which it occurs. They recognize that patterns observable at one scale may not be observable or exist at other scales, and some systems can only be studied indirectly as they are too small, too large, too fast, or too slow to observe directly. Students use orders of magnitude to understand how a model at one scale relates to a model at another scale. They use algebraic thinking to examine scientific data and predict the effect of a change in one variable on another (e.g., linear growth vs. exponential growth).

4. Systems and System Models

Progression Across the Grades
In grades pre-K–2, students can understand that objects and organisms can be described in terms of their parts and that systems in the natural and designed world have parts that work together.
In grades 3–5, students can understand that a system is a group of related parts that make up a whole and can carry out functions its individual parts cannot. They can also describe a system in terms of its components and their interactions.
In grades 6–8, students can understand that systems may interact with other systems; they may have sub-systems and be a part of larger complex systems. They can use models to represent systems and their interactions—such as inputs, processes, and outputs—and energy, matter, and information flows within systems. They can also learn that models are limited in that they only represent certain aspects of the system under study.
In grades 9–12, students can investigate or analyze a system by defining its boundaries and initial conditions, as well as its inputs and outputs. They can use models (e.g., physical, mathematical, computer models) to simulate the flow of energy, matter, and interactions within and between systems at different scales. They can also use models and simulations to predict the behavior of a system, and recognize that these predictions have limited precision and reliability due to the assumptions and approximations inherent in the models. They can also design systems to do specific tasks.

5. Energy and Matter: Flows, Cycles, and Conservation

Progression Across the Grades
In grades pre-K–2, students can observe that objects may break into smaller pieces, be put together into larger pieces, or change shapes.
In grades 3–5, students can learn that matter is made of particles and energy can be transferred in various ways and between objects. Students observe

the conservation of matter by tracking matter flows and cycles before and after processes and recognizing that the total weight of substances does not change.
In grades 6–8, students can learn that matter is conserved because atoms are conserved in physical and chemical processes. They also learn that, within a natural or designed system, the transfer of energy drives the motion and/or cycling of matter. Energy may take different forms (e.g., energy in fields, thermal energy, energy of motion). The transfer of energy can be tracked as energy flows through a designed or natural system.
In grades 9–12, students can learn that the total amount of energy and matter in closed systems is conserved. They can describe changes of energy and matter in a system in terms of energy and matter flows into, out of, and within that system. They also learn that energy cannot be created or destroyed. It only moves between one place and another place, between objects and/or fields, or between systems. Energy drives the cycling of matter within and between systems. In nuclear processes, atoms are not conserved, but the total number of protons plus neutrons is conserved.

6. Structure and Function

Progression Across the Grades
In grades pre-K–2, students can observe that the shapes and stability of structures of natural and designed objects are related to their functions.
In grades 3–5, students can learn that different materials have different substructures, which can sometimes be observed, and that substructures have shapes and parts that serve functions.
In grades 6–8, students can model complex and microscopic structures and systems and visualize how their function depends on the shapes, composition, and relationships among its parts. They analyze many complex natural and designed structures and systems to determine how they function. They design structures to serve particular functions by taking into account properties of different materials and how materials can be shaped and used.
In grades 9–12, students can investigate systems by examining the properties of different materials, the structures of different components, and their interconnections to reveal the system's function and/or solve a problem. They infer the functions and properties of natural and designed objects and systems from their overall structure, the way their components are shaped and used, and the molecular substructures of their various materials.

7. Stability and Change

Progression Across the Grades
In grades pre-K–2, students can observe that some things stay the same while other things change, and things may change slowly or rapidly.
In grades 3–5, students can measure change in terms of differences over time, and observe that change may occur at different rates. Students learn some systems appear stable, but over long periods of time they will eventually change.
In grades 6–8, students can explain stability and change in natural or designed systems by examining changes over time, and considering forces at different scales, including the atomic scale. Students learn changes in one part of a system might cause large changes in another part, systems in dynamic equilibrium are stable due to a balance of feedback mechanisms, and stability might be disturbed by either sudden events or gradual changes that accumulate over time
In grades 9–12, students can understand that much of science deals with constructing explanations of how things change and how they remain stable. They quantify and model changes in systems over very short or very long periods of time. They see some changes are irreversible, and negative feedback can stabilize a system, while positive feedback can destabilize it. They recognize that systems can be designed for greater or lesser stability.

8. Interdependence of Science, Engineering, and Technology

Progression Across the Grades
In grades pre-K–2, students can understand that science and engineering involve the use of tools to observe and measure things.
In grades 3–5, students can describe how science and technology support each other. Tools and instruments are used to answer scientific questions, while scientific discoveries lead to the development of new technologies.
In grades 6–8, students can identify that engineering advances have led to important discoveries in virtually every field of science, and that scientific discoveries have led to the development of entire industries and engineered systems. Science and technology drive each other forward.
In grades 9–12, students can understand that science and engineering complement each other in the cycle known as research and development (R&D). Many R&D projects may involve scientists, engineers, and others with wide ranges of expertise.

9. Influence of Engineering, Technology, and Science on Society and the Natural World

Progression Across the Grades
In grades pre-K–2, students can understand that every human-made product is designed by applying some knowledge of the natural world and is built by using natural materials. Taking natural materials to make things also makes an impact on the environment.
In grades 3–5, students can describe that people's needs and wants change over time, as do their demands for new and improved technologies. Engineers improve existing technologies or develop new ones to increase their benefits, decrease known risks, and meet societal demands. When new technologies become available, they can bring about changes in the way people live and interact with one another.
In grades 6–8, students can understand that all human activity draws on natural resources and has both short and long-term consequences, positive as well as negative, for the health of people and the natural environment. The uses of technologies and any limitations on their use are driven by individual or societal needs, desires, and values; by the findings of scientific research; and by differences in such factors as climate, natural resources, and economic conditions. Technology use varies over time and from region to region.
In grades 9–12, students can describe how modern civilization depends on major technological systems, such as agriculture, health, water, energy, transportation, manufacturing, construction, and communications. Engineers continuously modify these systems to increase benefits while decreasing costs and risks. New technologies can have deep impacts on society and the environment, including some that were not anticipated. Analysis of costs and benefits is a critical aspect of decisions about technology.

The Nature of Science in Curricula

An additional goal for pre-K–12 STE education is a scientifically and technologically literate person who can understand the nature of scientific knowledge. Indeed, the key consistent characteristic of scientific knowledge across the disciplines is that scientific knowledge itself is open to revision in light of new evidence.

The NRC *Framework* summarizes the nature of science in the following statement:

> Epistemic knowledge is knowledge of the constructs and values that are intrinsic to science. Students need to understand what is meant, for example, by an observation, a hypothesis, an inference, a model, a theory, or a claim and be able to distinguish among them.
>
> NRC, 2012, p. 79

Well-designed curricula should give students the opportunity to develop an understanding of the enterprise of science as a whole. A key challenge for curricula is how to explain both the natural world and what constitutes the formation of adequate, evidence-based scientific explanations. To be clear, this perspective complements but is distinct from students engaging in scientific and engineering practices in order to enhance their knowledge and understanding of the natural world.

The basic understandings about the nature of science include:

1. Scientific investigations use a variety of methods.
2. Scientific knowledge is based on empirical evidence.
3. Scientific knowledge is open to revision in light of new evidence.
4. Scientific models, laws, mechanisms, and theories explain natural phenomena.
5. Science is a way of knowing.
6. Scientific knowledge assumes an order and consistency in natural systems.
7. Science is a human endeavor.
8. Science addresses questions about the natural and material world.

The first four of these understandings are closely associated with practices and the second four with crosscutting concepts. The Nature of Science matrix from NGSS, presented in the two tables below, presents specific nature of science perspectives that can be integrated into curriculum and instruction for each grade span.

Students can also be engaged in learning about the nature of science through study of scientists and their work. Even though specific knowledge about these men and women is not included in the standards and will not be subject to state assessment, students should learn about their lives and discoveries, in order to provide them with greater insight into the real-life work of science and to inspire them to pursue educational and career opportunities in STE fields. By way of example, students should be able to recognize and discuss major scientific figures, such as Niels Bohr, Nicolaus Copernicus, Marie Curie, Charles Darwin, Albert Einstein, Galileo Galilei, Johannes Kepler, Gregor Mendel, Isaac Newton, Louis Pasteur, James Watson, Francis Crick, and Rosalind Franklin.

Conclusion

The utility of crosscutting concepts and nature of science will be realized when curriculum developers and teachers develop lessons, units, and courses that use these themes to tie together the broad diversity of STE core ideas and practices. Doing so can help students organize and make sense of relationships across disciplines and to engage in authentic STE.

[This appendix draws from and is an adaptation of the NGSS, Appendices G, H, and J.]

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Understandings about the Nature of Science (Practices)				
Categories	**Pre-K–2**	**3–5**	**Middle School**	**High School**
Scientific Investigations Use a Variety of Methods	• Science investigations begin with a question. • Scientists use different ways to study the world.	• Science methods are determined by questions. • Science investigations use a variety of methods, tools, and techniques.	• Science investigations use a variety of methods and tools to make measurements and observations. • Science investigations are guided by a set of values to ensure accuracy of measurements, observations, and objectivity of findings. • Science depends on evaluating proposed explanations. • Scientific values function as criteria in distinguishing between science and non-science.	• Science investigations use diverse methods and do not always use the same set of procedures to obtain data. • New technologies advance scientific knowledge. • Scientific inquiry is characterized by a common set of values that include: logical thinking, precision, open-mindedness, objectivity, skepticism, replicability of results, and honest and ethical reporting of findings. • The discourse practices of science are organized around disciplinary domains that share exemplars for making decisions regarding the values, instruments, methods, models, and evidence to adopt and use. • Scientific investigations use a variety of methods, tools, and techniques to revise and produce new knowledge.
Scientific Knowledge Is Based on Empirical Evidence	• Scientists look for patterns and order when making observations about the world.	• Science findings are based on recognizing patterns. • Scientists use tools and technologies to make accurate measurements and observations.	• Science knowledge is based upon logical and conceptual connections between evidence and explanations. • Science disciplines share common rules of obtaining and evaluating empirical evidence.	• Science knowledge is based on empirical evidence. • Science disciplines share common rules of evidence used to evaluate explanations about natural systems. • Science includes the process of coordinating patterns of evidence with current theory. • Science arguments are strengthened by multiple lines of evidence supporting a single explanation.
Scientific Knowledge Is Open to Revision in Light of New Evidence	• Science knowledge can change when new information is found.	• Science explanations can change based on new evidence.	• Scientific explanations are subject to revision and improvement in light of new evidence. • The certainty and durability of science findings varies. • Science findings are frequently revised and/or reinterpreted	• Scientific explanations can be probabilistic. • Most scientific knowledge is quite durable but is, in principle, subject to change based on new evidence and/or reinterpretation of existing evidence. • Scientific argumentation is a mode of logical discourse used to clarify the strength of relationships between ideas and evidence that

Understandings about the Nature of Science (Practices)				
Categories	**Pre-K–2**	**3–5**	**Middle School**	**High School**
			based on new evidence.	may result in revision of an explanation.
Science Models, Laws, Mechanisms, and Theories Explain Natural Phenomena	• Scientists use drawings, sketches, and models as a way to communicate ideas. • Scientists search for cause and effect relationships to explain natural events.	• Science theories are based on a body of evidence and many tests. • Science explanations describe the mechanisms for natural events.	• Theories are explanations for observable phenomena. • Science theories are based on a body of evidence developed over time. • Laws are regularities or mathematical descriptions of natural phenomena. • A hypothesis is used by scientists as an idea that may contribute important new knowledge for the evaluation of a scientific theory. • The term "theory" as used in science is very different from the common use outside of science.	• Theories and laws provide explanations in science, but theories do not, with time, become laws or facts. • A scientific theory is a substantiated explanation of some aspect of the natural world, based on a body of facts that has been repeatedly confirmed through observation and experiment, and validated by the science community before it is accepted. If new evidence is discovered that the theory does not accommodate, the theory is generally modified in light of this new evidence. • Models, mechanisms, and explanations collectively serve as tools in the development of a scientific theory. • Laws are statements or descriptions of the relationships among observable phenomena. • Scientists often use hypotheses to develop and test theories and explanations.

Understandings about the Nature of Science (Crosscutting Concepts)				
Categories	**Pre-K–2**	**3–5**	**Middle School**	**High School**
Science Is a Way of Knowing	• Science knowledge helps us know about the world.	• Science is both a body of knowledge and processes that add new knowledge. • Science is a way of knowing that is used by many people.	• Science is both a body of knowledge and the processes and practices used to add to that body of knowledge. • Science knowledge is cumulative and many people, from many generations and nations, have contributed to science knowledge. • Science is a way of knowing used by many people, not just scientists.	• Science is both a body of knowledge that represents a current understanding of natural systems and the processes used to refine, elaborate, revise, and extend this knowledge. • Science is a unique way of knowing and there are other ways of knowing. • Science distinguishes itself from other ways of knowing through use of empirical standards, logical arguments, and skeptical review. • Science knowledge has a history that includes the refinement of, and changes to, theories, ideas, and beliefs over time.
Scientific Knowledge Assumes an Order and Consistency in Natural Systems	• Science assumes natural events happen today as they happened in the past. • Many events are repeated.	• Science assumes consistent patterns in natural systems. • Basic laws of nature are the same everywhere in the universe.	• Science assumes that objects and events in natural systems occur in consistent patterns that are understandable through measurement and observation. • Science carefully considers and evaluates anomalies in data and evidence.	• Scientific knowledge is based on the assumption that natural laws operate today as they did in the past and they will continue to do so in the future. • Science assumes the universe is a vast single system in which basic laws are consistent.
Science Is a Human Endeavor	• People have practiced science for a long time. • Men and women of diverse backgrounds are scientists and engineers.	• Men and women from all cultures and backgrounds choose careers as scientists and engineers. • Most scientists and engineers work in teams. • Science affects everyday life. • Creativity and imagination are	• Men and women from different social, cultural, and ethnic backgrounds work as scientists and engineers. • Scientists and engineers rely on human qualities, such as persistence, precision, reasoning, logic, imagination and creativity. • Scientists and engineers are guided by habits of mind, such as intellectual honesty, tolerance of ambiguity, skepticism and openness to new ideas.	• Scientific knowledge is a result of human endeavor, imagination, and creativity. • Individuals and teams from many nations and cultures have contributed to science and to advances in engineering. • Scientists' backgrounds, theoretical commitments, and fields of endeavor influence the nature of their findings. • Technological advances have influenced the progress of science and science has influenced advances in technology. • Science and engineering are influenced by society and society is influenced by science and engineering.

Understandings about the Nature of Science (Crosscutting Concepts)				
Categories	**Pre-K–2**	**3–5**	**Middle School**	**High School**
		important to science.	• Advances in technology influence the progress of science and science has influenced advances in technology.	
Science Addresses Questions About the Natural and Material World	• Scientists study the natural and material world.	• Science findings are limited to what can be answered with empirical evidence.	• Scientific knowledge is constrained by human capacity, technology, and materials. • Science limits its explanations to systems that lend themselves to observation and empirical evidence. • Science knowledge can describe consequences of actions but is not responsible for society's decisions.	• Not all questions can be answered by science. • Science and technology may raise ethical issues for which science, by itself, does not provide answers and solutions. • Science knowledge indicates what can happen in natural systems—not what should happen. The latter involves ethics, values, and human decisions about the use of knowledge. • Many decisions are **not** made using science alone, but rely on social and cultural contexts to resolve issues.