How Can the History and Philosophy of Science Contribute to Contemporary U.S. Science Teaching

Friday, 07 December 2012

Sponsored by the National Science Foundation's Division of Research on Learning in Formal and Informal Settings under REESE grant 1205273. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

Organized by the School of Education and the Center for Philosophy and History of Science at Boston University.

Framing the Learning/Teaching of Science and Nature of Science:

- Practices-Core Ideas-Crosscutting Concepts

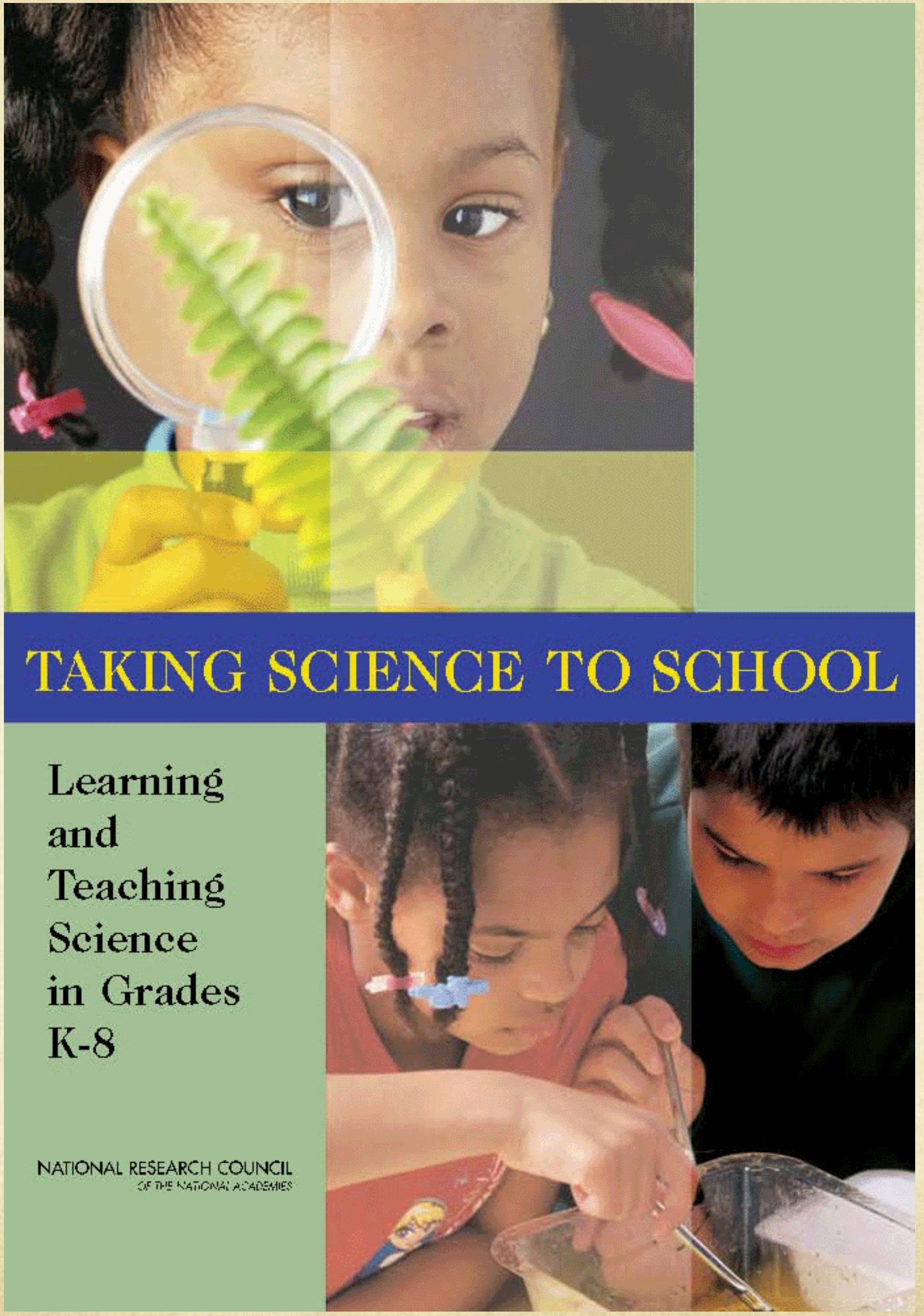
Boston University December 7, 2012

Richard A. Duschl
Penn State University
University Park, PA

Current US STEM Education Agenda

- Taking Science to School (NRC, 2007)
- Science Standards for College Success (College Board, 2009)
- The Opportunity Equation (Carnegie Foundation, 2009)
- A Framework for K-12 Science Education: Practices, Crosscutting Concepts and Core Ideas   NRC (2011)
- Successful STEM Education: A Workshop Summary (NRC, 2011)
- Monitoring Progress in K-12 STEM Education: A Nation Advancing? (NRC, 2012)
- Discipline-Based Education Research: Understanding and Improving Learning in Undergraduate Science & Engineering (NRC 2012)
- Education for Life and Work: Developing Transferable Knowledge and Skills in the 21st Century (NRC, 2012)

Taking Science to School

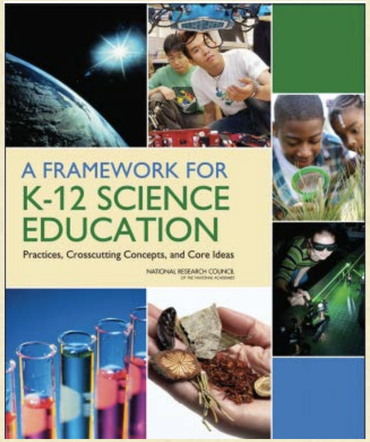


4 Strands of Science Proficiency

- Understanding Scientific Explanations – understand central concepts and use them to build and critique explanations.
- Generating Scientific Evidence – generating and evaluating evidence as part of building and refining models and explanations of the natural world.
- Reflecting on Scientific Knowledge – understand that doing science entails searching for core explanations and the connections between them.
- Participating Productively in Science – understand the norms for presenting scientific arguments and evidence and practice productive social interactions with peers around classroom science investigations.

NRC, 2008 Ready, Set, Science!

A Framework to guide changes in K-12 science



NEXT GENERATION SCIENCE STANDARDS

- Assessments
- Curricula
- Instruction
- Teacher Development

NEXT GENERATION SCIENCE STANDARDS

NEXT GENERATION SCIENCE STANDARDS

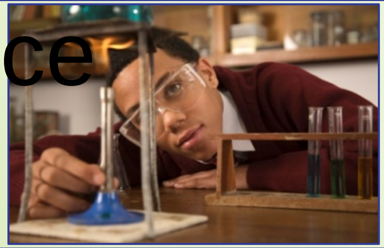
Science and Engineering Practices

Disciplinary Core Ideas

Crosscutting Concepts

For States By States

Vision for Next Generation Science Standards



Next Generation Science Standards for Today's Students and Tomorrow's Workforce:

Through a collaborative, state-led process, new K–12 science standards are being developed that will be rich in content and practice, arranged in a coherent manner across disciplines and grades to provide all students an internationally benchmarked science education. The NGSS will be based on the *Framework for K–12 Science Education* developed by the National Research Council.

NEXT GENERATION SCIENCE STANDARDS

BOX ES.1
The Three Dimensions of the Framework

1. Scientific and Engineering Practices	**3. Disciplinary Core Ideas**
1. Asking questions (for science) and defining problems (for engineering) 2. Developing and using models 3. Planning and carrying out investigations 4. Analyzing and interpreting data 5. Using mathematics and computational thinking 6. Constructing explanations (for science) and designing solutions (for engineering) 7. Engaging in argument from evidence 8. Obtaining, evaluating, and communicating information **2. Crosscutting Concepts** 1. Patterns 2. Cause and effect: Mechanism and explanation 3. Scale, proportion, and quantity 4. Systems and system models 5. Energy and matter: Flows, cycles, and conservation 6. Structure and function 7. Stability and change	<u>Physical Sciences</u> PS 1: Matter and its interactions PS 2: Motion and stability: Forces and interactions PS 3: Energy PS 4: Waves and their applications in technologies for information transfer <u>Life Sciences</u> LS 1: From molecules to organisms: Structures and processes LS 2: Ecosystems: Interactions, energy, and dynamics LS 3: Heredity: Inheritance and variation of traits LS 4: Biological evolution: Unity and diversity <u>Earth and Space Sciences</u> ESS 1: Earth's place in the universe ESS 2: Earth's systems ESS 3: Earth and human activity <u>Engineering, Technology, and the Applications of Science</u> ETS 1: Engineering design ETS 2: Links among engineering, technology, science, and society

What Is Science?

Science is built up of facts as a house is of stones, but a collection of facts is no more a science than a pile of stones is a house. *-Henri Poincare*

- Science involves:
  - Building/Refining theories and models
  - Collecting and analyzing data from observations or experiments
  - Constructing & Critiquing arguments
  - Using specialized ways of talking, writing and representing phenomena
- Science is a social phenomena with unique norms for participation in a community of peers.

NRC, 2007 Taking Science to School

History of Thinking about NOS

Science is about *Hypotheses* testing and reasoning deductively from *Experiments*
(1900 to 1960) – The Positivist Turn

Science is about *Theory* building and revision
(1960 to 1980) – The Historical Turn

Science is about *Model* building and revision
Models stand between Experiment and Theory
(1970 – present) – The Naturalistic Turn

The Cognitive Basis of Science

Carruthers, Stich, & Siegal, Eds. (2003) Cambridge University Press

- "What makes science possible? Specifically, what features of the human mind, of human cognitive development, and of human social arrangements permit and facilitate the conduct of science?"
- Such questions are interdisciplinary in nature "requiring co-operation between philosophers, psychologists, and others in the social and cognitive sciences (and are) as much about the psychological underpinnings of science as they are about science itself."

- [P]hilosophy of science had been conducted in a relatively *a priori* fashion…with philosophers of science just thinking about what scientists *ought* to do, rather than about what they actually *do* do. This all began to change in the 1960s and 1970s, when philosophy of science took its' so-called "historical turn." [emphasis in original] (Carruthers et al., 2002, p. 3)

- It became important, then, to see science, too, as a natural phenomenon, somehow recruiting a variety of natural processes and mechanisms–both cognitive and social–to achieve its results. Philosophers of science began to look, not just to history, but also to cognitive psychology in their search for an understanding of scientific activity. (Carruthers et al., 2002, p. 4)

Transitional Steps to Naturalized Philosophy of Sciences

- Emergence of the Social Pragmatic View of Language via accounts of the 'Causal Theory of Reference' and the failure of formal inductive syntactical structures (heuristic principles) to explain explanations.
- Emergence of Cognitive Psychologies as the dominance of Behaviorism recedes leading first to Sense Data and second to Theory of Mind
- Emergence of Philosophy of Biology to introduce evolutionary ideas about emergence and the treatment of anomalous data.
- Emergence of History of Science and the subsequent shift from accounts of older history to accounts of newer or contemporary history to establish growth of knowledge mechanisms.
- Emergence of 'Practices' and Epistemic Cultures – cognitive and social – as a basis interpreting the building and refining of scientific knowledge and methods.
- Complex Systems and NOS – a reconsideration of emergent properties

3 Part Harmony Learning Goals

- Conceptual "guiding conceptions for what we need to know"
- Epistemic "rules for what counts as knowledge"
- Social "communicating & representing ideas, evidence and explanations"
- Duschl, R. (2008). Science education in 3 part harmony: Balancing conceptual, epistemic and social learning goals. *Review of Research in Education, V32.*

Science and Engineering Practices

Disciplinary Core Ideas

Crosscutting Concepts

NEXT GENERATION SCIENCE STANDARDS

For States By States

Categories for Empirical Reasoning[a]	*Scientific Practices*[b]	*Verbs*[b]
Planning, Designing Data Acquisition	Selection of observation tools and schedule; Selection of measurement tools and units of measurement; Selection of question(s); Understanding interrelationships among central science concepts; Use central science concepts to build and critique arguments	Presents, Asks, Responds, Discusses, Revises, Expands, Challenges, Critiques. Knows, Uses, Interprets
Data Collection	Observing systematically, Measuring accurately, Structuring data, Setting standards for quality control, Posing controls, Forming conventions	Examines, Reviews, Evaluates, Modifies, Generates,
Evidence (Data Use)	Use results of measurement and observation; Generating evidence; Structuring evidence, Construct and defend arguments; Mastering conceptual understanding;	Extends, Refines, Revises, Decides, Categorizes,
Patterns (Modeled Evidence)	Presenting evidence; Mathematical modeling; Evidence-based model building; Masters use of mathematical, physical and computational tools;	Represents, Evaluates, Predicts, Discovers, Interprets, Manipulates, Build, Refines, Analyzes, Models,
Explanation	Posing theories; Conceptual-based models building; Search for core explanation; Considering alternatives; Understands how evidence and arguments based on evidence are generated; Revises predictions and explanations; Generates new and productive questions;	Builds, Refines, Represents, Interacts,

MS.LS-NSA Natural Selection and Adaptations
Students who demonstrate understanding can: **a. Analyze patterns in data for changes in the fossil record that provide evidence of the history of life on Earth.** **b. Construct explanations for the anatomical similarities and differences between fossils of once-living organisms and organisms living today.** [Clarifying Statement: Students should use the record of evolutionary descent between ancient and modern-day organisms.] **c. Construct explanations for why most individual organisms, as well as some entire species of organisms, that lived in the past were never fossilized.** [Assessment Boundary: The process of fossilization is not treated in any detail in life sciences but addressed in Earth sciences.] **d. Analyze graphical displays to compare patterns of similarities in the embryological development across different species to identify relationships not evident in the fully formed anatomy.** [Assessment Boundary: Limited to general characteristics of embryological development among species.] **e. Communicate explanations for how genetic variations of traits in a population increase some individuals' probability of surviving and reproducing in a specific environment, which tends to increase these traits and suppress other traits in the population.** **f. Use mathematical models to explain how natural selection over many generations results in changes within species in response to environmental conditions that increase or decrease certain traits in a population.** [Clarifying Statement: Students should explain trends based on data of populations of organisms over time showing trends in numbers of individuals with specific traits.] **g. Obtain and evaluate information about how two populations of the same species in different environments have evolved to become separate species.** [Clarifying Statement: Students evaluate information for the degree to which it provides evidence that two populations of the same species in different environments have evolved.] **h. Analyze and interpret accumulated historical evidence of patterns in the fossil record that document the existence, diversity, extinction, and change of many life forms throughout the history of life on Earth under the assumption that natural laws operate today as they did in the past.**

Performance Expectations with DCI Organization
“Natural Selection and Adaptations”

Science and Engineering Practices

Developing and Using Models

Modeling in 6–8 builds on K–5 and progresses to developing, using and revising models to explain, explore, and predict more abstract phenomena and design systems.

- Pose models to describe mechanism at unobservable scales. (f)

Analyzing and Interpreting Data

Analyzing data in 6–8 builds on K–5 and progresses to extending quantitative analysis to investigations, distinguishing between correlation and causation, and basic statistical techniques of data and error analysis.

- Consider limitations of data analysis, such as measurement error, and seek to improve precision and accuracy of data with better technological tools and methods such as multiple trials. (h)
- Distinguish between causal and correlational relationships. (a)
- Use graphical displays to analyze data in order to identify linear and nonlinear relationships. (d),(h)

Using Mathematics and Computational Thinking

Mathematical and computational thinking at the 6–8 level builds on K–5 and progresses to identifying patterns in large data sets and using mathematical concepts to support explanations and arguments.

- Use mathematical concepts such as ratios, averages, basic probability, and simple functions, including linear relationships to analyze data. (f)

Constructing Explanations and Designing Solutions

Constructing explanations and designing solutions in 6–8 builds on K–5 experiences and progresses to include constructing explanations and designing solutions supported by multiple sources of evidence consistent with scientific knowledge, principles, and theories.

- Base explanations on evidence and the assumption that natural laws operate today as they did in the past and will continue to do so in the future. (b)
- Apply scientific reasoning to show why the data are adequate for the explanation or conclusion. (c)

Obtaining, Evaluating, and Communicating Information

Obtaining, evaluating, and communicating information in 6–8 builds on 3–5 and progresses to evaluating the merit and validity of ideas and methods.

- Generate and communicate ideas using scientific language and reasoning. (e)
- Gather, read, and explain information from appropriate sources and evaluate the credibility of the publication, authors, possible bias of the source, and methods used. (g)

Disciplinary Core Ideas

LS4.A: Evidence of Common Ancestry and Diversity

- Fossils are mineral replacements, preserved remains, or traces of organisms that lived in the past. Thousands of layers of sedimentary rock not only provide evidence of the history of the Earth itself but also of changes in organisms whose fossil remains have been found in those layers. (a),(h)
- The collection of fossils and their placement in chronological order (e.g., through the location of the sedimentary layers in which they are found or through radioactive dating) is known as the fossil record. It documents the existence, diversity, extinction, and change of many life forms throughout the history of life on Earth. Because of the conditions necessary for their preservation, not all types of organisms that existed in the past have left fossils that can be retrieved. (c), (h)
- Anatomical similarities and differences between various organisms living today and between them and organisms in the fossil record, enable the reconstruction of evolutionary history and the inference of lines of evolutionary descent. (b)
- Comparison of the embryological development of different species also reveals similarities that show relationships not evident in the fully-formed anatomy. (d)

LS4.B: Natural Selection

- Genetic variations among individuals in a population give some individuals an advantage in surviving and reproducing in their environment. This is known as natural selection. It leads to the predominance of certain traits in a population, and the suppression of others. (e),(f)

LS4.C: Adaptation

- Adaptation by natural selection acting over generations is one important process by which species change over time in response to changes in environmental conditions. (g),(f)
- Traits that support successful survival and reproduction in the new environment become more common; those that do not become less common. Thus, the distribution of traits in a population changes. (f)
- In separated populations with different conditions, the changes can be large enough that the populations, provided they remain separated (a process called reproductive isolation), evolve to be separate species. (g)

Crosscutting Concepts

Patterns

- Patterns can be used to identify cause and effect relationships. (b),(h)
- Graphs and charts can be used to identify patterns in data. (a),(d)

Cause and Effect

- Cause and effect relationships may be used to predict phenomena in natural or designed systems. Phenomena may have more than one cause, and some cause and effect relationships in systems can only be described using probability. (c),(e),(f)

Stability and Change

- Small changes in one part of a system might cause large changes in another part. (g)

Connection to Nature of Science

Scientific Knowledge Assumes an Order and Consistency in Natural Systems

- Science assumes that objects and events in natural systems occur in consistent patterns that are understandable through observation. (h)

Performance Expectations with Topics Organization

MS.ESS1 Earth's Place in the Universe

Students who demonstrate understanding can:

SS.a. Use models of the sun, Earth, and moon system to explain the cyclic occurrences of tides, eclipses, and observable constellations. [Clarifying Statement: Earth's rotation describes the occurrence of tides; the revolution of Earth around the sun explains the annual cycle of the apparent movement of the constellations in the night sky; the moon's revolution around Earth explains the cycle of spring/neap tides and the occurrence of eclipses; the moon's elliptical orbit explains the occurrence of total and annular eclipses.] [Assessment Boundary: Kepler's 2nd and 3rd Laws of orbital motion are not assessed at this level.]

SS.b. Use models of the sun and Earth system to explain the seasons are a result of Earth's tilt and are caused by the differential intensity of sunlight on different areas of Earth across the year. [Clarifying Statement: The revolution of Earth around the sun and the tilt of Earth's axis explain seasons.]

SS.c. Construct and use models of the solar system to describe the locations and motions of the planets as observed from Earth. [Clarifying Statement: Models should include physical models (e.g., distance along a football field) or conceptual models (e.g., proportions relative to their school or state).]

SS.d. Construct an argument for the formation of the solar system based on space exploration evidence of the composition, structure, and motions of solar system bodies. [Clarifying Statement: Evidence that our solar system formed from a disk of dust and gas drawn together by gravity includes: (1) the similarity between the direction of rotation of the sun, the orbits of the planets, and the directions of the rotations of planets, (2) patterns of impact craters on planetary surfaces, (3) the composition of meteorites, some of which show the make-up of the early solar system, and (4) the distribution of mass in the solar system with metal/rock-rich objects close to the sun and ice-rich objects far from the sun.] [Assessment Boundary: Students are not responsible for details of the sequence of the evolution of the solar system, such as the timing of the late-heavy bombardment period.]

SS.e. Obtain, evaluate, and communicate information that shows how science limits questions and explanations about (1) the expansion and scale of the universe to support the Big Bang theory and (2) the location of Earth with respect to the Milky Way galaxy to natural material systems only. [Clarifying Statement: Evidence for the Big Bang at this level involves the size of the universe and the fact that most galaxies are moving away from each other, demonstrating an expansion of the universe over the past 13.7 billion years. Communication can be orally or in writing.] [Assessment Boundary: Evidence for the Big Bang involving the composition of the universe and the Doppler shift of starlight is not to be assessed at this level.]

HE.a. Apply scientific reasoning using geoscience evidence from past centuries to show how scientific findings about the relative ages of a sequence of Earth events have been debated and revised. [Clarifying Statement: Evidence can be field evidence or demonstrative representations (e.g., model of geologic cross-sections); "events" may include sedimentary layering, fossilization, folding, faulting, igneous intrusion, and/or erosion.]

HE.b. Use models of the geologic time scale to describe the relative timing of major events in Earth's history. [Clarifying Statement: Models may be temporal (e.g., Earth's history scaled to a day or year) or spatial (e.g., scaled to a football field) and show the spacing of events is larger for Earth's early history. Major events could include the formation of mountain chains and ocean basins, evolution and extinction of particular living organisms, volcanic eruptions, periods of massive glaciation, and the development of watersheds and rivers through glaciation and water erosion.] [Assessment Boundary: Memorization of specific periods or epochs of the geologic timescale is not intended.]

EIP.b. Use models to explain correlations between plate motions and plate boundaries recognizing that geosciences processes occurring now have occurred throughout Earth's history. [Clarifying Statement: Models include maps of plate motions and representations of plate boundaries. Divergent boundaries include both mid-ocean ridges and continental rifts; convergent boundaries include both subduction zones and continent-continent collisions. Geosciences processes could include the Principle of Uniformitarianism.]

EIP.c. Use models to explain the convective cycling of matter between Earth's surface and deep mantle and its connection with plate tectonics. [Clarifying Statement: Patterns of mantle convection and its surface expression (plate tectonics) are largely driven by the sinking of cold and dense sheets of ocean lithosphere at subduction zones, forming ocean trenches. Rock is returned to the surface via volcanism at continental rifts and oceanic ridges, as well as at hot spot volcanoes. Explanations should include the formation of mid-ocean ridges and ocean trenches.] [Assessment Boundary: Details of thermodynamic and radiogenic processes that drive mantle convection are not required.]

Science and Engineering Practices

Developing and Using Models
Modeling in 6–8 builds on K–5 and progresses to developing, using and revising models to explain, explore, and predict more abstract phenomena and design systems.

- Use and construct models to predict, explain, and/or collect data to test ideas about phenomena in natural or designed systems, including those representing inputs and outputs. (SS.a),(SS.b),(SS.c)
- Use models to predict, explain, and/or collect data to test ideas about phenomena in natural or designed systems, including those representing inputs and outputs. (HE.b),(EIP.b),(EIP.c)

Engaging in Argument from Evidence
Engaging in argument from evidence in 6–8 builds from K–5 experiences and progresses to constructing a convincing argument that supports or refutes claims for either explanations or solutions about the natural and designed world.

- Use oral and written arguments supported by empirical evidence and reasoning to support or refute an argument for a phenomenon or a solution to a problem. (SS.d)

Obtaining, Evaluating, and Communicating Information
Obtaining, evaluating, and communicating information in 6–8 builds on 3–5 and progresses to evaluate the merit and validity of ideas and methods.

- Read critically using scientific knowledge and reasoning to evaluate data, hypotheses, conclusions, and competing information. (SS.e)

Constructing Explanations and Designing Solutions
Constructing explanations and designing solutions in 6–8 builds on K–5 experiences and progresses to include constructing explanations and designing solutions supported by multiple sources of evidence consistent with scientific knowledge, principles, and theories.

- Apply scientific reasoning to show why the data are adequate for the explanation or conclusion. (HE.a)

Connection to Nature of Science

Scientific findings are open to further consideration with new evidence or a competing theory.

- Science findings vary in its certainty and durability. (HE.a)
- Science findings may be revised based on evaluation of procedures, evidence, reasoning and explanations. (HE.a)

Disciplinary Core Ideas

ESS1.A: The Universe and Its Stars

- Patterns of the apparent motion of the sun, the moon, and stars in the sky can be observed, described, predicted, and explained with models. (SS.a),(SS.b)
- The universe began with a period of extreme and rapid expansion known as the Big Bang. (e)
- Earth and its solar system are part of the Milky Way galaxy, which is one of many galaxies in the universe. (SS.c),(SS.e)

ESS1.B: Earth and the Solar System

- The solar system consists of the sun and a collection of objects, including planets, their moons, and asteroids that are held in orbit around the sun by its gravitational pull on them. (SS.d)
- This model of the solar system can explain tides, eclipses of the sun and the moon, and the motion of the planets in the sky relative to the stars. (SS.a)
- Earth's spin axis is fixed in direction over the short-term but tilted relative to its orbit around the sun. The seasons are a result of that tilt and are caused by the differential intensity of sunlight on different areas of Earth across the year. (SS.b)

ESS1.C: The History of Planet Earth

- The geologic time scale interpreted from rock strata provides a way to organize Earth's history. Major historical events include the formation of mountain chains and ocean basins, evolution and extinction of particular living organisms, volcanic eruptions, periods of massive glaciation, and the development of watersheds and rivers through glaciation and water erosion. (HE.b),(secondary to HE.d)
- Analyses of rock strata and the fossil record provide only relative dates, not an absolute scale. (HE.a),(secondary to HE.d)
- *Tectonic processes continually generate new ocean sea floor at ridges and destroy old sea floor at trenches.* (EIP.b),(EIP.c) (*HS.ESS1.C GBE*)

Crosscutting Concepts

Patterns

- Patterns can be used to identify cause and effect relationships. (SS.a),(SS.b)
- Patterns in rates of change and other numerical relationships can provide information about natural and human designed systems. (EIP.b)

Energy and Matter

- Within a natural or designed system, the transfer of energy drives the motion and/or cycling of matter. (EIP.c)

Scale, Proportion, and Quantity

- Time, space, and energy phenomena can be observed at various scales using models to study systems that are too large or too small. (SS.c),(SS.e),(HE.a),(HE.b)

Interdependence of Science, Engineering, and Technology

- Engineering advances have led to important discoveries in virtually every field of science and scientific discoveries have led to the development of entire industries and engineered systems. Science and technology drive each other forward. (SS.d)

Connection to Nature of Science

Science is limited it can only address questions about the natural material world.

- Scientific knowledge is constrained by human capacities and technologies. (SS.e)
- Science limits its explanations to systems that lend themselves to observation and empirical evidence. (SS.e)

Scientific knowledge assumes order and regularity in natural systems.

- Science assumes that objects and events in natural systems occur in consistent patterns that are understandable through observation and measurement. (EIP.b)

NOS Matrix Heading

- One goal of science education is to help students understand the nature of scientific knowledge. This matrix presents eight major themes and grade level understandings about the nature of science. Four themes extend the scientific and engineering practices and four themes extend the crosscutting concepts. These eight themes are presented in the left column. The matrix describes learning outcomes for the themes at grade bands for K-2, 3-5, middle school, and high school. Appropriate learning outcomes are expressed in selected performance expectations and presented in the foundation boxes throughout the standards.

NOS Crosscutting Concepts

- Science is a Way of Knowing
- Scientific Knowledge Assumes an Order and Consistency in Natural Systems
- Science is a Human Endeavor
- Science Addresses Questions About the Natural and Material World.

NOS Practices

- Scientific Investigations Use a Variety of Methods
- Scientific Knowledge is Based on Empirical Evidence
- Scientific Knowledge is Open to Revision in Light of New Evidence
- Science Models, Laws, Mechanisms, and Theories Explain Natural Phenomena

New View of NOS
C^3 & SPs

- Emphasizes the role of models and data construction in the scientific practices of theory development.
- Sees the scientific community, and not individual scientists, as an essential part of the scientific process.
- Sees the cognitive scientific processes and scientific practices as a distributed system that includes instruments, forms of representation, and agreed upon systems for communication and argument.