STEM Learning in Context: Opportunities and Challenges from Climate Science and
Engineering

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Abstract

The paper provides an overview of recent developments in the geosciences and geographical
sciences and in the learning sciences to set out implications for the design of climate change and
engineered systems education models. Current educational contexts such as the *Next Generation
Science Standards* and the recently published 'Geoscience Literacy' introduce perspectives on
secondary and postsecondary STEM education and STEM education policies and practices. A
review of 'learning sciences' serves to segue into a new frontier in STEM education research –
learning progressions. Learning progressions provide a viable context and mechanism for
advancing 'Engineering in Earth Systems' STEM curriculum, instruction, and assessment
models. That is, climate change education projects should adopt a Learning Progressions
perspective on developing curriculum, instruction, and assessment models. Climate science and
engineered system contexts in local, regional, as well as national domains represent an extremely
rich and motivating forum for STEM education and STEM policy education. The research
agenda will be complex given the new images we have of science, of capable young learners, of
science and engineering participatory practices and of the importance of context when
motivating the understanding and evaluation of climate science knowledge and engineered
systems.

Introduction

Among the K-16 science options, the Earth sciences are at one and the same time familiar
and abstract to learners. The ground beneath our feet, the 'dirt'/soil we dig in, the flowing
streams, the sandy beaches, the highway road cuts revealing strata, the rocks encountered on
walks all contribute to our familiar sense perception view of the Earth and geoscience processes.
From very early ages, however, we also confront phenomena that do not present themselves in
concrete meaningful ways. Consider the movement of the sun through the sky, the changing
images of the moon, the eclipses of the moon, the more rare eclipses of the sun, the flooding of
streams and rivers, the wrath of earthquakes, droughts, tornadoes and hurricanes, the mining and
extraction of ores, and the existence of voids and of massive formations below the surface. Many
of these events are hard to comprehend because of the spatial or temporal scales and the
interacting mechanisms involved both within and across Earth systems (e.g., biosphere,
lithosphere, atmosphere, hydrosphere, cryosphere). There are numerous challenges both for
understanding such events and for communicating evidence and explanations of such events.

The National Academy of Sciences convened the Committee on Grand Challenges in Environmental Sciences to address the question, what challenges exist for future generations of citizens? The outcome was the report *Grand Challenges in Environmental Sciences* (National Academy Press, 2001), which identified eight grand challenges for which there is a need for significant infusion of research over the next two decades. Challenges such as:

- Biogeochemical cycles: understanding how human activity is perturbing the six nutrient cycles of carbon, oxygen, hydrogen, nitrogen, sulfur, and phosphorus which has impacts on climate change, CO_2 concentrations, acid rain, and chlorofluorocarbons (CFC)
- Biological diversity and ecosystem functioning: understanding the regulation and functional consequences of biological diversity, which has impacts on rates of species extinction, threats to biological diversity, and controls on biological diversity
- Hydrological forecasting: understanding and predicting changes in freshwater resources and the environment caused by floods, droughts, sedimentation, and contamination, which threatens freshwater ecosystems

In 2000 the Directorate for Geosciences at the National Science Foundation (NSF) reported on a long-range planning activity to evaluate opportunities and requirements for research, education and infrastructure. In the foreword of the report *NSF Geoscience beyond 2000: Understanding and Predicting Earth's Environment and Habitability*, we learn that "the geosciences have enjoyed major advances in understanding the Earth systems and the complex interactions among the various elements: atmosphere, ocean, land surface and biosphere. These dramatic advances are now providing new and enhanced opportunities for geosciences, in combination with sister disciplines, to provide important services to the nation through predictions of potentially harmful or beneficial events" (NSF, 2000).

More recently, the NRC Board on Earth Sciences and Resources formed the Committee on Strategic Directions for the Geographical Sciences in the Next Decade. The report – *Understanding the Changing Planet: Strategic Directions for the Geographical Sciences* (NRC, 2010) – which is organized around eleven Strategic Research Questions (e.g., How are we changing the physical environment of the Earth's surface? How can we best preserve biological diversity and protect endangered ecosystems? How are climate and other environmental changes affecting the vulnerabilities of coupled Human-Environment systems?) also outlines a set of challenges: "Many of the central challenges of the 21st century are tied to changes to the spatial organizations and character of the landscapes and environments of Earth's surface as populations move, natural resources are depleted, and climate shifts" (p1). Then there is the importance of understanding the impacts (e.g., scientific, economic, ethical, etc.) engineered systems have in mitigating and changing the vulnerabilities of Human-Environmental systems. The report also makes very clear that "[t]echnological developments and changing research priorities have inspired the rapid growth of geographical sciences over the past two decades" (p1) such that a broader set of researchers (e.g., engineers, economists, biologists, epidemiologists, geologists) now engage in the geographical sciences.

When we consider these science and engineering challenges in terms of our K-16 education system, there are two agendas. First, the education system must sustain a STEM workforce of students to serve as the next generation of technicians, scientists, engineers, and mathematicians, who will help research the grand challenges. Second and just as important, the education system must also develop a scientifically literate citizenship that can make informed policy decisions about acting on the grand challenges. Economic, policy, and social issues will

converge around the grand challenges forcing citizens to make decisions that will impact the future of their resources. These two desired outcomes will require a new vision of STEM education for K-12 students, one that will provide deeper and broader learning experiences. Deeper in the sense that understanding the complexity of climate science models and engineering design solutions necessitates acquiring a range of core disciplinary ideas and a suite of science and engineering practices. Broader in the sense that these ideas and practices are inherently interdisciplinary as well as cognitively and epistemically challenging when working between and among the S, 'science', the T, 'technology', the E, 'engineering' and the M, 'mathematics.' The consideration of climate science and engineering systems as a means for coordinating and forging STEM engagements represents a robust context for the design of curriculum, instruction, and assessment models that can address the two educational challenges.

The paper begins with a section on recent developments in the geosciences and geographical sciences and their implications for the design of climate change and engineered systems education. The next section examines the run up to and the writing and dissemination of the *Next Generation Science Standards*, followed by a review of the recently published 'Geoscience Literacy' documents, which reflect a backward looking perspective on secondary and postsecondary STEM education and thus a challenge to current STEM education policies and practices. Next, an overview of the now dominant 'learning sciences' perspective for teaching and learning is presented. Here the focus is on the new perspectives and images of what constitutes effective science learning and teaching environments. The review of the 'learning sciences' sets up a discussion of what represents a new frontier in STEM education research – learning progressions (LP). Next is an 'Engineering in Earth Systems' section that examines the developing learning progression frameworks in Earth systems contexts. Here technical language and frameworks being used in LP research are introduced. The intent is to demonstrate and argue that climate change education projects should adopt a LP perspective in developing curriculum, instruction, and assessment models.

Earth Systems and Engineered Systems: STEM Educational Challenges

The access to new data and new forms of data that geographical information systems (GIS) provide has contributed to new conceptualizations of the mechanics of Earth systems and new inquiry methods. Changes in the geosciences and geographical science indeed have been dramatic in the last 20 years. The reconceptualization of Earth science as *Earth systems science* is a very recent development. Early on the pursuit of geographical and geoscience knowledge was closely aligned with the applied problems of commerce and industry and with a keen interest in obtaining an accurate history of the earth. In the US, state and national geological surveys showed the way with geologists in the field getting up close and personal with rocks and structures (McPhee, 1998; Pettijohn, 1975). Mining and mapping the resources and terrains of regions and establishing the places and paths for trains, ships and trucks to reach the resources needed for an industrial and increasingly global society was the pragmatic goal that once dominated the geosciences. Such an orientation to the geosciences, I would argue, continues to dominate the curriculum materials of K-12 earth science programs and courses of study.

Advances in technology, especially computing power for simulations, visualizations, and sensors, and in scientific understanding coupled with a growing global sense of responsibility have shifted both the focus and the methods of the Earth sciences. With respect to focus, the trend for several decades has been toward a systems analysis of the Earth. With respect to

methods, the trend is toward model-based science. These two trends have strong implications for the inclusion of engineering and engineered systems as a context for STEM education. Models are increasingly being used for exploring and explaining the complex dynamics and structures of the earth's surface. Issues of and questions about habitability and sustainability of Planet Earth are paramount for developing better predictive models that can, in turn, be used to shape policy and management.

Next Generation Science Standards

In addition to the changes that an Earth systems science perspective has on framing research and development in geosciences and geographical sciences, the systems perspective also has implications for educational practices and policy. Recently, two influential National Research Council (NRC) reports have set a new course for US science education. The two reports are *Taking Science to School: Learning and teaching science in grades K-8* (NRC, 2007a) and *A Framework for K-12 Science Education: Practices, Crosscutting Concepts and Core Ideas* (NRC, 2012). The *Framework* is being used to guide the develop of the *Next Generation Science Standards,* which is a States led initiative to establish from one source (i.e., *Framework*) standards and assessments for teaching and learning science in K-12.[1] In addition to the NRC, the other four development partners are the Council of State Science Supervisors, the National Science Teachers Association, the American Association for the Advancement of Science, and Achieve, Inc. Achieve is a NGO set up by the National Governors Association and Council of Chief State School Officers to develop, disseminate and implement common core standards in K-12 education. The English Language Arts and Mathematics standards have been released and adopted by 48 states. The *Next Generation Science Standards* are under development and public review at the time of writing this report.

The recommendations from the NRC *Framework* have three implications for STEM education using climate sciences and engineered systems. One is that science education should be coordinated around three dimensions - crosscutting concepts, core ideas, and practices (see Figure 1). Two, is that the practices should represent both science and engineering. Three, the alignment of curriculum, instruction and assessment should be implemented through the development of learning progressions that function across grade bands.

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[1] Current State state sciences are based on either the NRC *National Science Education Standards* or AAAS *Benchmarks for Science Literacy*. While the content coverage in both documents has been shown to have a 90% agreement, one salient difference is the grade level objectives in the Standards vs. the grade band objectives (e.g., K-2, 3-5, 6-8, 9-12) in the Benchmarks. These differences impact the design of State curriculum standards and science exams.

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	<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
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>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

Figure 1 – Three Dimensions of the Framework. NRC (2011) *A Framework for K-12 Science Education: Crosscutting concepts, scientific practices and core ideas, Executive Summary* (p ES3*).*

There exist, however, concomitant and competing science literacy efforts that I maintain work in opposition to the 3 Dimensions perspective found in the *Framework.* More specifically, the geosciences community has recently published four 'Literacy' documents that set out essential principles and fundamental concepts for each disciplinary domain:

- **Climate Literacy:** The Essential Principles of Climate Science, *A climate-oriented approach for learners of all ages.* (2009).
- **Ocean Literacy:** The Essential Principles of Ocean Sciences K-12, *An ocean-oriented approach to teaching science standards.* (2007).
- **Earth Science Literacy:** The Big Ideas and Supporting Concepts of Earth Science (2009).
- **Atmospheric Science Literacy:** Essential Principles and Fundamental Concepts of Atmospheric Science (2008).

The attention to Earth systems sciences is laudable and the involvement of geoscientists is commendable. There are, however, several salient disconnects between the Geoscience documents and the NRC *Framework* that I argue need to be resolved as we consider how climate change education initiatives are enacted and how STEM domains (i.e., engineered systems) find a place in the K-16 curriculum.

Standards Alignment: One disconnect is grounding the four geoscience literacy documents in the dated National Science Education Standards (1996) and the AAAS Benchmarks (1993) frameworks. The writing and development of the above Literacy documents

took place concurrently with the writing and development of the several NRC synthesis research reports that were based on important earlier NRC research synthesis reports that inform learning and teaching science K-16:

- National Research Council (2009). *Learning Science in Informal Environments:People, Places, and Pursuits.*
- National Research Council, (2007). *Taking Science to School: Learning and teaching science in grades K-8.*
- National Research Council. (2006). *Learning to think spatially: GIS as a support system in the K-12 curriculum.*
- National Research Council. (2006). *America's Lab Report: Investigations in High School Science.*
- National Research Council. (2005). *Systems for State Science Assessment.*
- National Research Council. (2002). *Learning and Understanding: Improving advanced study of mathematics and science in US high schools.*
- National Research Council. (2001). *Knowing What Students Know: The science and design of educational assessment.*
- National Research Council. (1999). *How People Learn.*

For the scientists and science educators who authored the *Literacy* pamphlets to ignore the above documents is a serious oversight. What it has led to is a conflation and confusion of what actually counts as Big Ideas and Scientific Practices with in the Geosciences community. The research from the NRC reports concludes that *Standards* and *Benchmarks* have been found to contain far too many disconnected learning goals. Looking across all four of the Geoscience Literacy documents there are way too many fundamental concepts – e.g., 76 in *Earth Science Literacy* alignment and 44 in Ocean Literacy alignment. The *Ocean Literacy: Overview Matrix for K-12* and the *Earth Science Literacy* matrix reveals how the alignment process to the old Standards leads to 1) an overemphasis on disconnected conceptual learning, 2) an under emphasis on the supporting and applied contexts of science learning (e.g., Science & Technology; Personal & Social Perspectives) and 3) an omission of science practices and crosscutting concepts. The Standard sub-category 'Abilities necessary to do scientific inquiry K-12' only appears in 4 of the 44 fundamental concepts for the Ocean Literacy matrix and does not appear at all in the *Earth Science Literacy* matrix! The wrong messages are being sent to secondary and post-secondary teachers and faculty.

Separation of Content and Practice: Adopting education models wherein *knowing* is separated from *doing* is anathema to learning research. When learning science principles take place independent of engagement with the cognitive and social practice contexts within which the concepts are used and applied, meaningful learning and reasoning are stifled. The main message from the above NRC reports on science learning is NOT to separate the learning of concepts from the practices, processes, and skills whereby the concepts are developed, refined, used, and evaluated. Instead learning should parallel the science and engineering practices used by STEM practitioners.

Writing Team Orientations - The third disconnect found among the four Geoscience literacy documents and the NRC documents is the composition of the authoring teams. The Geoscience teams were exclusively natural scientists and higher education faculty from the four domains – climate, ocean, atmosphere, Earth, while the NRC synthesis reports and frameworks

were written by natural scientists, cognitive scientists, learning scientists and science educators. The differences are how and the extent to which the science-orientation merges with the student-orientation; i.e., how students come to learn and understand the science and engineering principles and practices

    Learning Progressions: The fourth disconnect between the two sets of documents is the omission in the Geoscience publications and the inclusion in the NRC publications of information about the development of scientific knowledge and practices across grade levels in K-12 and between and within courses in post-secondary. Such sequencing and coherence of teaching and learning is a major orientation for STEM education research and development and comes under the headings of learning progressions and teaching sequences.[2] The study of Earth systems and engineering systems involves complex thinking concerning complex interacting systems. Understanding how Earth systems work and the impact humans have on Earth systems requires a great deal more than knowing the essential principles. Equally important is the development and coordination of the essential principles (Core Ideas), the crosscutting concepts and the scientific practices (see Figure 1). The important shift is away from an emphasis on merely knowing to an emphasis on using knowledge.

Learning Sciences and Science Learning: An Overview

    This section presents a selected review of the literature on science learning and teaching that is guided by the concomitant and ongoing developments in cognitive sciences and science studies. The focus of the overview is on a few salient topics that capture the vibrant debates and current challenges among researchers that have emerged when the study of science learning, science discourse, and scientific inquiry is examined in contexts (e.g., conceptual, epistemological, and social), at different ages (e.g., preschool, K-8, secondary, college, adult), and in various learning environments (e.g., formal and informal).

    STEM learning when viewed generally as the growth of knowledge has many parallels with scientific and engineering inquiry among scientists as a set of knowledge building and refining activities and practices. These activities and practices progress from experiments onto models and explanatory theories. Models are seen as cognitive tools that sit between experiments and theory (Giere, 1988, 2002; Nersessian, 2002, 2008). What has come to gain traction is the view of science and science learning as fundamentally a model building and refining enterprise. The synthesis research report *TSTS* (NRC, 2007a) takes the position that the teaching and learning of science should be based on an image of science that sees the growth of knowledge as involving the following epistemic and social practices:

1.   Building theories and models
2.   Constructing arguments
3.   Using specialized ways of talking, writing, and representing phenomena

This tripartite perspective on school science reflects a synthesis of ideas about the growth of knowledge and the nature of scientific reasoning from the learning sciences community and the science studies community.

    The learning sciences emerged from the earlier constructivist theories of learning and from pioneering research in the cognitive sciences. Our deeper understanding of how

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[2] Research reviews on learning progressions in science, learning trajectories in mathmatics, and teaching sequences can be found in Corcoran, Mosher and Rogat (2009); Daro, Mosher and Corcoran (2011); Duschl, Maeng and Sezen (2011); and Alonzo and Gotwals (2012).

children's thinking is fundamentally different from that of adults coupled with richer understandings of expertise, representation, reflection, problem solving and thinking provided a foundation for a major tenet of the learning sciences: "students learn deeper knowledge when they engage in activities that are similar to the everyday activities of professionals who work in a discipline" (Sawyer, 2006, p. 4). Similarly, philosophers started to realize that any attempts to account for the growth of scientific knowledge or theory change needed to view inquiry through the natural human mental processes and human modes of acquiring knowledge. This philosophical perspective aligns somewhat with research on informal learning that reveals the importance of participation structures and the development of practices in culturally valued activities (Cole, 1996; NRC, 2009). Focusing on scaffolding, apprenticeship, legitimate peripheral participation and guided participation, informal learning researchers provided "broader units of analysis…these views move beyond the study of individuals alone to consider how learning occurs within enduring social groups such as families and communities" (Bransford et al., 2006, p. 24).

Advances in our understandings about learning have occurred in tandem with our richer understandings about the growth of knowledge within STEM disciplines. Essentially, we are learning how to learn with respect to the natural and designed world and about learning itself. Ideas from interdisciplinary research communities labeled *learning sciences* and *science studies* are extending our understandings of science learning, science practices, scientific knowledge, and scientific discourse (Duschl, 2008; Duschl & Grandy, 2008). Cognitive, historical, sociological, and anthropological studies of individuals working in knowledge building contexts reveals the importance of practices to the professional activities in these knowledge growth communities. With respect to the scientific disciplines, cognitive models of science (Giere, 1988; Goldman, 1986; Kitcher, 1993; Thagard, 1992) coupled with sociocultural models of science (Knorr-Cetina, 1999; Kuhn, 1996; Longino, 1990, 2002) have established the importance that models and modeling, visual representations, knowledge exchange mechanisms and peer interactions have in the advancement and refinement of knowledge and in the growth of scientific knowledge. In brief, doing science takes place in complex settings of cognitive, epistemic and social practices.

Research on learning is moving away from a focus on general principles of learning to a focus on developing domain specific knowledge, e.g., the epistemic, cognitive, social, and cultural factors that influence the growth of knowledge in STEM domains. New images of science coupled with new images of learning have in rapid succession decade after decade since 1950 led to new perspectives about the foundations of science and thus of STEM education. The synthesis research report on science learning, *Taking Science to School (TSTS)* (NRC, 2007a), recommends that science learning be organized around select conceptual knowledge frameworks and practices that, in turn, are coordinated around core content and learning progressions. What the current research in cognitive development and philosophy of mind suggests is that very young children have a surprising capacity for reasoning and prior knowledge in select domains (Keil, 1989; Subrhmanyam, Gelman, & Lafosse, 2002). The current research on cognitive development and reasoning in science also demonstrates that context matters both in terms of content, learning environment, and learning goals (Atran, 2002; Koslowski & Thompson, 2002; Siegal, 2002). That is, learning is linked to the domain within which learning is taking place and dependent on the acquisition of select practices and ways of representing and communicating science ideas and critiques. Consequently, *core knowledge* learning and *learning progressions*

designs for the alignment of curriculum, instruction, and assessment are seen as robust areas for future science learning research.

Embedding research on science learning within specific contexts (e.g., core ideas and crosscutting concepts in Earth Systems, Ocean, Climate, Atmospheric, Energy Literacy) has produced valuable insights into pathways or trajectories of learning in the disciplines (Catley, Reiser, & Lehrer, 2005; Smith et al., 2006). However, the research on learning in contexts challenges many of the *received views* of child and adolescent science learning. These domain general views assume that development involves broad mental structures that facilitate mastery of a variety of tasks. Examining the research on children's learning and capacities for representation provides insights on how domain-specific learning frameworks can serve as a foundation for model building and systems thinking in science.

Children's engagements in pretend play, in which one object stands in for another (a spoon for a rocket), is a beginning notion of symbolism—one thing can represent another. Early understandings of words as representing objects or actions are also indicative of emerging symbolic capacities. Engagement with measurement and data representation can be introduced early on as the PrePS$^©$ curriculum (Gelman & Brenneman, 2004) demonstrates. Preschool children can sort objects based on size, color, shape, or other features and then be guided to display this information in the form of lists, tables and simple graphs. Children can compare measurements, for example shoe size and height of children in different classes (and ages), as well as chart growth in these quantities over time (Gelman & Brenneman, 2004). Understandings about counting, measuring, and illustrating patterns provide a necessary foundation for developing more sophisticated notions of descriptive statistics and data modeling that can be introduced in formal schooling.

Research on elementary students' ability to measure and represent data suggest that young children can engage in productive discussions about aspects of an object to measure (e.g., how would one measure plant growth) and how these data should be graphically represented (Lehrer, Jaslow, & Curtis, 2003; Lehrer & Schauble, 2000a, 2000b, 2002). Lehrer and Schauble (2004) employed a design study approach to investigating the development of student understanding of natural variation through learning and reasoning about the statistical concept of distribution in a data-modeling context. The focus of the research was to document the learning of students' understanding of variation when the students are exposed to good instructional experiences. In order to facilitate fifth grade students' understanding of variation, students engaged in an immersion unit comprised of activities that focused on the growing of batches of native plants. A goal was to find out how the plants would change over time and be influenced by different growth conditions. Over a two-month period, students' reasoning related to an understanding of the concepts "distribution" and "natural variation" significantly improved. This depth of understanding developed out of students' experiences in generating, evaluating, and revising models of data recorded on the growth of these native plants. The students' invented and teachers' guided representations of data served as a focus for discussions about simple statistical qualities of data, as well as the values of different forms of representations for illustrating different features of data patterns (Lehrer & Schauble, 2004).

The extensive research on infants and young children's cognitive development underscores the multitude of knowledge resources and reasoning capabilities children bring to formal schooling. Young learners are anything but empty minds. They are, within effective instructional conditions (Lehrer & Schauble, 2002), capable of noticing patterns and attributes in the natural world, linking patterns and attributes to science concepts, developing explanations of

natural phenomena, and reasoning about abstract ideas in meaningful and productive ways. However, if the context and focus of STEM learning is on acquiring too many principles that are disconnected to practices or use with other principles, then learning suffers.

Whether or not we chose to capitalize on learner's emerging scientific reasoning abilities and further develop them depends on how we construe the goals of science learning and how such learning outcomes can be achieved. A focus on understanding the doing of science and how scientific knowledge is developed and evaluated will entail building on students' emerging capacities for representation, model-building, casual reasoning, and the like. Three critical aspects of the nature of contexts and situations that are embedded in most views and research on learning within domain specific contexts are issues of *authenticity, collaboration,* and *inquiry* (Blumenfeld et al., 2006). Authenticity, within the context of STEM learning, focuses on embedding the learning within the learners' everyday world and within the practices of the discipline. Collaboration, within the context of STEM learning, encourages the sharing and contrasting of ideas with other individuals within a community who are engaged in similar tasks and who have similar aims. Finally, inquiry motivates STEM learners to engage in problem stating and solving activities, which require planning, synthesis and evaluation skills using relevant domain specific content knowledge.

If the focus of science education is on the accumulation of scientific facts and essential principles devoid of using that information to propose explanations and predictions, then it is not clear how one might capitalize on the emerging understandings. Thus, the NRC research and policy documents argue for a STEM education that focuses on the investigative and discourse practices embedded in model/theory building/refining (e.g., knowing and doing). Research informs us that implementing such a building and refining learning environment allows students to generate significant conceptual resources that can, and should be, used as leverage for developing more sophisticated understandings of the scientific and engineering enterprises throughout schooling.

Grounded strongly in perspectives from philosophy of science, philosophy of mind, and developmental psychology, the interdisciplinary approach to understanding STEM learning, knowing, and doing has established in no uncertain terms that learning, cognition, and reasoning are contingent on context and content. The strong recommendation from *TSTS* is that the teaching of conceptual knowledge should not be independent of science and design practices. In short, our understandings of the growth of scientific knowledge and reasoning are grounded both philosophically and psychologically (Carruthers et al., 2002). Each domain has contributed to our understandings about *learning how to learn*. The emerging consensus is that learning and teaching ought to be grounded in and informed by conceptual, epistemological, and social structures and practices. Within science education, changes in our understandings of what is science—the nature of science—have influenced our understandings of what is involved in learning and doing science. Conversely, our understandings of what is involved in learning and doing science have influenced our understandings about the nature of science.

Learning Progressions and Developmental Pathways

The preceding learning science research overview makes very clear that sequence and coherence in matters of learning are paramount. There are developmental pathways children need to follow to enhance both conceptual understandings and participation in essential discourses practices. In this section we examine in more detail the emerging research domain of

learning progressions in order to better understand how climate science and engineered systems might be folded into K-16 STEM education.

Taking Science To School (NRC, 2007a) makes the recommendation that science learning needs to be strongly grounded in model-based approaches that focus on the use and consideration of evidence for posing, building and refining models. Within the model-based learning/teaching approaches, quantitative reasoning and conceptual understandings can, along with other science and engineering practices, develop. Science and engineering practices are one of the three NRC Framework Dimensions (See Figure 1) and are an important component that includes the critique and communication discourse practices. Like the Core Ideas and Crosscutting concepts, the science and engineering practices require time to develop.

Thus, the recommendation in *TSTS,* in the NRC (2011) framework for science standards and in the NRC (2009) report *Engineering in K-12 Education* is that science learning be organized into longer sequences – learning progressions (LPs) - that serve as vertical pathways of learning across grade levels and as teaching sequences horizontally within any instructional year. The rationale is that facilitating the learning of core knowledge and practices that are critical for development of scientific knowledge and scientific reasoning is complex, takes time, and requires instruction-assisted development grounded in sound assessment practices. Thus, the content of LPs includes the core knowledge, the epistemic practices (e.g., science talk and argumentation), and the social practices (e.g., critique, communication and representation) that characterize a domain of science and/or engineering. The recommendation from *the National Research Council* is that:

> The core concepts used in this practice [learning progressions] would be dramatically fewer in number than those currently focused on or included in standards and curriculum documents. …[A] grade-level teacher would need to be concerned not only with the relevant "slice" of a given core idea in her particular grade, but also with the longer continuum of learning that K-8 students experience. Thus, teachers and science teacher educators…would need to build structures and social processes to support the exchange of knowledge and information related to core concepts across grade levels. (NRC, 2007b, p. 61)

The LPs approach to the design and alignment of curriculum, instruction, and assessment is grounded in domain-specific or core knowledge theories of cognitive development and learning as documented in recent National Research Council reports (NRC 1999; 2001, 2007a). Corcoran, Mosher, and Rogat (2009) convened several workshops of experts exploring LPs to look at two questions:

> What promise might LPs have for improving instruction in schools?
> What further might be required to make the promise real?

LPs are seen as empirically grounded and testable hypotheses about how students' understandings of and abilities to use core ideas grow and become more sophisticated over time. In an early review of LPs, 4 features were found to characterize them (Corcoran, et al, 2009):

1. Target core and generative disciplinary understandings and practices that merge science content with science practices.

2. They have lower and upper boundaries that describe entry assumptions and exiting expectations for knowing and doing.
3. They inform progress levels or steps of achievement.
4. They have purposeful curriculum and instruction that mediates targeted student outcomes.

The consideration of LPs represents a shift in emphasis away from teaching that focuses on what we know (e. g., facts and skills) to teaching that focuses on how did we come to know and develop scientific knowledge, as well as focusing on why we believe what we know over alternatives. Within the how and why approaches reside 'assessment for learning' opportunities to make thinking visible as students engage in talk and argumentation and in modeling and representation. The report by Corcoran et al. (2009) states that "progressions can play a central role in supporting the needed shift toward adaptive instruction" (p. 9) and that the following are seen as possible learning outcome benefits of establishing LPs:

- Provide a basis for setting standards that are tighter and more clearly tied to instruction.
- Provide reference points for assessment to report on levels of progress and thereby facilitate teacher interventions and instruction-assisted development.
- Inform the design of curricula that are aligned with progressing students (e.g., assessments for learning).

Unfortunately, the NRC (2009) report on *Engineering in K-12 Education* found that there "is no widely accepted vision of what K-12 engineering education should include or accomplish" and that this "lack of consensus reflects the ad hoc development of educational material in engineering" (p. 7). Commenting on the disconnectedness found in K-12 engineering curriculum content the committee stated that "it seems that no one has attempted to specify age-appropriate learning progressions in a rigorous or systematic way; this lack of specificity or consensus on learning outcomes and progression goes a long way toward explaining the variability and unevenness in the curricula" (p.8).

An examination of the growth of scientific knowledge as provided by longitudinal studies around LPs (Corcoran et al., 2009) and by science studies scholars (Nersessian, 2008) can provide some helpful insights on how to precede with the engineering curriculum content redesign agenda. Corcoran and Silander (2009) conducted a review of the effects different instructional strategies had on high school students' learning. The strategies included *interdisciplinary teaching, cooperative learning, problem-based learning, adaptive instruction, inquiry, and dialogic teaching.* The results found that creating well-designed student grouping strategies, allowing students to express their ideas and questions, and offering students challenging tasks were powerful strategies for advancing student learning. In addition, *adaptive instruction,* in which teachers use formative assessments to monitor how students vary in what they are learning and to adapt instruction in response to students' progress and needs, was found to be a strong factor that supports student learning.

A key component of LPs is the notion that instruction-assisted development, like adaptive instruction, is grounded in robust learning performances (Wilson, 2009) that serve as "assessments for learning" (Black & Wiliam, 1998). The LPs represent pathways of learning that are research based studies of students' progress on learning foundational knowledge, like the well researched learning pathway on matter and the atomic molecular theory (Smith, Carey, &

Wiser, 1985; Smith et al., 2006). The extant alternative is the selection of topics and sequences based on a logical analysis of content domains and personal experiences with teaching [e.g., the American Association for the Advancement of Science (2004) *Atlas of Science Literacy* and the scope and sequence curriculum frameworks common in national, state and local school districts].

In a review and analysis of learning progression and teaching sequence research, Duschl, Maeng and Sezen (2011) draw a distinction between 'Validation LPs' and 'Evolutionary LPs' (See Table 1). They argue that only the Evolutionary forms are conducting LP research that is attending to the development of foundational knowledge and to thorough descriptions of LP instruction assisted pathways. The Validation forms, while valuable (e.g., developing and testing assessment models; testing discourse strategies or instructional interventions), are only components or constituents of science learning and thus are better labeled as teaching sequences that can be precursors to, but are not learning progressions.

LP designs and research, whether evolutionary or validation, need to be longitudinal, following learners and learning across several grades or in case of postsecondary across courses. This eliminates as LP research the teaching sequence investigations that examine learning within single units that entail short durations of instruction, e.g., lesson sequences, immersion unit modules. Teaching sequences that focus on the conceptual demands of core idea domains but eschew the science practices are problematic. Typically such hypothetical learning progressions begin from reviews of strand maps, curriculum guides, or standards frameworks.

Canonical knowledge like that presented in the Geoscience Literacy pamphlets is not the same as learners' foundational knowledge. What drops out in many teaching-sequence formatted trajectories is the consideration of the inherently diverse learners' perspectives where the foundational knowledge resides. If the research studies conceptual development without also examining how learners use knowledge when engaged in a science practice(s), then the research should not be considered LP research. Considerations of knowledge use and its coupling with science practices are important criteria for LP research.

Table 1. Validation LPs and Evolutionary LPs

Validation LPs	Evolutionary LPs
• LP based on validating a standards-based progression: instruction as intervention • Theory-driven top/down approach	• LP based on sequencing of teaching experiments across multi-grades: instruction as refining progression • Evidence-driven bottom/up approach
• Upper anchors as college readiness • Uses assessments to confirm learning models • Progress variables steps and targets are fixed • Adopts a misconception-based 'Fix It' view of conceptual change instruction • Theory building as conceptual change • Domain general orientation to topic selection	• Upper anchors as targeted literacy • Uses assessments to explore learning models • Progress variable steps and targets are flexible • Adopts an intuition-based 'Work with It' view of conceptual change instruction • Model building as conceptual change • Domain specific orientation to topic selection

The climate science and engineering communities of researchers would benefit from analyses of the core ideas and practices that they use. The content of LPs—core ideas and practices—can also be informed by science studies research that examines the practices researchers and designers employ. Consider as an example the work of Nersessian (2008) that is extending her research program studying the cognitive basis of model-based reasoning in science (Nersessian, 2002). In her most recent research she is studying the cognitive practices of biomolecular scientists and biomedical engineers working together on interdisciplinary problems concerning cultivating/engineering tissues. The work is guided by the premise that "studying inquiry practices in research laboratories could lead to development of effective pedagogical strategies for improving the instructional laboratory" (2008, p. 72). In the context of cutting edge science, she maintains, everyone is a learner—undergraduates, Ph.D. candidates, post-doctoral researchers and lab directors. Nersessian refers to such contexts as "agentive learning environments" and found several significant features:

- With conceptual and methodological knowledge and skills distributed, everyone, even undergraduate students, make contributions.
- The organization is non-hierarchical – no one person is the expert, neophyte members can contribute and achieve legitimacy and identity.
- Interactional structures allow for membership routes into the laboratory that motivate learning.
- Multiple social support systems bolster resiliency in a research context that has frequent failures.

Commenting on the potential bridges from science labs to science classrooms and recognizing the differences, she writes, these contexts have "their own unique constraints and affordances that need to be figured into the development of strategies for learning and using

model-based reasoning. …[T]he point is that the *kinds of reasoning processes* should aim to approximate those of a scientist." (2008, p. 78).

Engineering in Earth Systems

The "Partnership for Education on Climate Change, Engineering Systems, and Society" takes as its focus **the interactions of climate change with engineered systems**. What we have here is a systems-within-systems problem, i.e., engineering systems addressing Earth systems geosciences. The conjecture is that climate change and society's responses to it will require enormous transformation of the engineered systems that make up the nation's technological infrastructure. Addressing this enormous challenge is appropriately seen as a long-term education and education policy agenda. The goal is catalyzing and transforming engineering education in K-12, science museums, and undergraduate engineering departments to prepare current and future engineers, policymakers, and the public to meet the challenges that climate change poses to engineered systems.

The complexity of the challenge is understood and acknowledge in the CCEP proposal 'Project Summary':

> Technically, there is an enormous need to develop educational platforms for both engineers and the public focused on the multiple, complex interactions between engineered systems and the Earth's climate system. Engineered systems stand at a critical juncture between humanity and climate change and must be designed, built, and managed in new ways in the face of climate change. At the same time, efforts to transform technological systems raise fundamental normative challenges for both engineers and broader publics, including complex trade-offs among the types and distribution of benefits, costs, and risks and potentials for building public trust, confidence, and engagement. New education must therefore fully integrate technical and normative learning, knowledge, and skills.

The shift to Earth Systems Science and to Complex Systems Thinking in recent decades has profoundly impacted our images of doing science and engineering. As an example, consider Duschl and Herbert's (2003) proposed guiding framework for the redesign of K-12 Earth science immersion units (i.e., 6-8 week long instructional blocks). As part of a project for an NSF Math and Science Partnership (MSP) involving 5 city school districts, partnerships between scientists and learning scientists were established and asked to outline the core ideas and core inquiry practices for biology, physics, chemistry and Earth science. Duschl and Herbert (2003) framed their report in terms of 1) three fundamental challenges in the learning of Earth sciences and 2) core ideas linked to the study of biogeochemical cycles. The proposed framework has a great deal in common with Earth/Space Science guidelines found in National Assessment of Educational Progress (NAEP), College Board, and Geoscience Literacy Principles (see Figure 2), all documents used to inform the development of the NRC Framework for K-12 Science Standards. Here it serves as an example of how educational efforts need to be construed, decomposed if you will, to attend to the big ideas and science practices that are representative of Earth Systems Science (ESS).

ESS Learning challenges – The learning challenges can be seen as the cognitive frameworks within which Earth systems scientists do science. The first learning challenge is the ability to **conceptualize natural Earth environments** as having boundaries and mechanisms for transferring and manipulating matter and energy within and across Earth systems. The second learning challenge is describing and explaining the **dynamic nature of Earth systems** through a characterization of system states over space and time with a focus on both steady-state and non-equilibrium conditions. The third learning challenge is **understanding complexity** and the **practices geoscientists use to study complexity**. Geoscience inquiry synthesizes across at least three principal sets of practices:

- Investigations involving simulations
- Investigations involving characterization of the properties and dynamics of natural systems
- Investigations involving laboratory experimentation where conditions can be controlled and causal relationships established

Together the 3 sets of inquiry practices help develop quantitative and conceptual models of Earth systems. Hence, quantitative reasoning and model-based reasoning as conducted through the building and refining of models becomes central to understanding the essential principles in the geoscience literacy documents. In turn, these practices need to be essential components of STEM education.

Core ideas – Duschl and Herbert (2003) posit that the core concepts (i.e., crosscutting concepts of the NRC K-12 Framework), which are fundamental to reasoning and inquiring in the geosciences, include **scale** (deep time and deep space), **energy** (gravitational, thermal, tidal and solar sources – evident by **temperature/pressure** conditions), and **matter transformation**. Each is important for understanding the actions in and on the **biogeochemical cycles** (e.g., water, carbon, nitrogen, rock) that occur in Earth systems. Thus, when considering a reconceptualization of Earth science education curricula in terms of Earth systems and in terms of science and engineering practices, learning goals need to address the development of increasing sophistication with knowing and using the tenets of deep space and time, of Earth systems science, and of boundaries within biogeochemical cycles. In addition, the emergence of new tools and technologies (e.g., GIS) for simulations, visualizations, and modeling have significant implications for developing a framework to guide the design of immersion units that function across the K-16 science experience.

NAEP, College Board Earth Science, and Geoscience Literacy Principles

NAEP SCIENCE 2009 (NAGB, 2009)	College Board's 2009 Standards for College Success (Earth Science)	Geoscience Literacy Principles
Earth in Space and Time: Objects in the Universe	• **Systems:** Planetary Evolution	
Earth in Space and Time: History of Earth	• **History:** Relative and Absolute Dating • **History:** Rock and Fossil Records	**Earth:** Earth is 4.6 billion years old.
Earth Structures: Properties of Earth Materials	• **Processes:** Rock-Forming Environment	
Earth Structures: Tectonics	• **Processes:** Tectonism	**Earth:** Earth is continuously changing.
Earth Systems: Energy in Earth Systems	• **Processes:** Earth's Surface • **Processes:** Energy Transfer • **Systems:** Atmosphere as a System • **Systems:** Oceans as a System • **Systems:** Lithosphere as a System	**Earth:** Earth is a complex system of interacting rock, water, air, and life. **Earth:** Earth is the water planet. **Ocean:** Earth has one big ocean with many features. **Atmos:** Earth has a thin atmosphere that sustains life. **Atmos:** Energy from the Sun drives atmospheric processes. **Atmos:** Earth's Atmosphere continuously interacts with the other components of the Earth System. **Atmos:** Atmospheric circulations transport matter and energy. **Climate:** The Sun is the primary source of energy for Earth's climate system. **Climate:** Climate is regulated by complex interactions among components of the Earth System.
Earth Systems: Climate and Weather	• **Processes:** Weather Processes • **Systems:** Climate	**Ocean:** The ocean is a major influence on weather and climate **Atmos:** Earth's atmosphere changes over time and space, giving rise to weather and climate. **Climate:** Climate varies over space and time through both natural and man-made processes.
Earth Systems: Biogeochemical Cycles	• **Matter&Energy:** Water Cycle • **Matter & Energy:** Carbon Cycle	**Earth:** Life evolves on a dynamic Earth and continuously modifies Earth. **Ocean:** The ocean supports a great diversity of life and ecosystems. **Climate:** Life on Earth depends on, is shaped by, and affects climate.
	• **Humans:** Humans and Natural Resources • **Humans:** Humans and Natural Hazards • **Humans:** Humans' Impact on the Environment	**Earth:** Humans depend on Earth for resources. **Earth:** Natural hazards pose risks to humans. **Earth:** Humans significantly alter the Earth. **Ocean:** The ocean makes Earth habitable. **Ocean:** The ocean and humans are inextricably interconnected. **Atmos:** Earth's atmosphere and humans are inextricably linked. **Climate:** Human activities are impacting the climate system. **Climate:** Climate change will have consequences for the Earth System and human lives.

Figure 2 – Geoscience Literacy Principles compared to NAEP 2009 Science Framework and College Board Standards for College Success Earth Science Topics.

Another rich example of the pedagogical challenges we face in reforming STEM around Earth systems concepts and the development of quantitative and model-based reasoning comes from the learning progression research conducted by Charles A. Anderson, Michigan State University, and colleagues (Gunkel, Covitt, & Anderson, 2009; Mohan & Anderson, 2009; Mohan, Chen, & Anderson, 2009). Their work represents an example of integrating science concepts and science practices in LP studies with an emphasis on core understandings of scientific principles that are situated in practice learning. The LP conceptual domains are carbon

and water cycling with learning goals targeting comprehending global warming and helping learners become environmentally literate.

The researchers considered environmental science literacy as the interrelation among discourse on environmental issues, practices of explanation/prediction in the events of carbon/water cycling, and knowledge about complex system of carbon and water cycling. In the LP for carbon cycling the focus is on joining domains of knowledge with practices of explaining and predicting, e.g., students' accounts of mechanisms to generate, transform, and oxidize organic carbon tied to students' reasoning about using the knowledge within mechanisms. The water cycling LP integrated scientific principles with explaining/predicting practices about the movement of water and substances in water to represent accounts of students' reasoning and to ascertain levels of performance.

Descriptions of learning progressions involve establishing a beginning point and an ending point that can span months, semesters, or years. *TSTS* refers to the beginning point as the 'lower anchor,' which represents the knowledge children bring with them to school. This beginning knowledge is often grounded in sensory-based observations of commonly occurring natural events. In this way the lower anchor disciplinary concepts of LPs are said to be accessible to learners since they have some awareness of the phenomenon. The 'upper anchor' represents the expectations we have of students learning at the end of the LP. That is, what students should know and be able to do.

The lower anchors of LPs often consist of macroscopic events, which are easily visible or related to students' everyday-experience or accounts. This characteristic of LPs ensures the target concepts of LPs are accessible to learners. For example, Mohan et al.'s (2009) learning progression on carbon cycling was based on five focused macroscopic events familiar to students: plants growth, animal growth, animal movement and weight loss, decay, and burning. The lower anchor of this LP focuses on intuitive accounts that macroscopic events are the result of natural tendencies by differing agents and enablers. In other words, the growth of plants is a natural process enabled by food, water, or sunlight. Mohan et al. labeled this kind of reasoning and accounts as *force-dynamic,* which is closely related to children's informal everyday experiences and discourse. Using macroscopic events and considering the force-dynamic accounts as the lower anchor make this LP appear to be accessible to early years' learners.

Lehrer and Schauble (2012), in a component LP for learning practices used in evolution, recognize that the theory of evolution has several everyday knowledge entailments that could be productive resources for developing scientific explanations. The entailments are observable and measurable differences (1) between or within species, (2) over time in individual growth or population fluctuations, and (3) between organisms' structural features and habitat. The lowest levels of the three entailments involve describing qualitative differences, observing and describing the current state of an organism or group of organisms, and posing questions about where an organism lives. Thus, the lower anchor of learning performances is accessible in that it is related to basic practices for understanding the evolutionary concept through variability, change, and ecology.

The upper anchor represents the learning goals of the LP. Again, the emphasis is on using knowledge and practices. *TSTS* represents upper anchors as the successive adoption of more accurate scientific understanding and increasingly sophisticated science practices that together establish societal expectations for science literacy. The upper anchor goals and performance expectations will obviously vary depending on the targeted ending grade, e.g., 5th, 8th, 10th, etc.

Not unlike the accessibility issue for the lower anchor, the upper anchor has to also attend to issues of appropriately targeted learning goals.

In the carbon cycling LP, Mohan et al. (2009) has as the 12th grade upper anchor the acquisition of knowledge and information that is needed by scientifically literate citizens to interpret environmental systems and to judge human impact on environmental systems in terms of chemical models. Thus, they identify as the upper anchor a suite of scientific principles or accounts regarding chemical processes, e.g., connected systems of generating organic carbon (**photosynthesis**), transforming organic carbon (**biosynthesis and digestion**), and oxidizing organic carbon (**cellular respiration and combustion**). The accounts are labeled '*qualitative model-based accounts*' and contain descriptions of chemical changes constrained by foundational principles of matter/energy conservation and energy degradation. While this upper anchor may appear to be highly abstract, the learning pathway across multiple grades begins with accessible macroscopic characteristics in the lower anchor. Through iterative design based research implementations and refinements of the curriculum sequence, the researchers are working on reorganizing the intricate network of domain-specific concepts and are doing so in the context of scientific decisionmaking.

Between the lower and the upper anchor there are the intermediate steps, or what some researchers refer to as the 'messy middle.' Wiser et al (2009) and Smith et al (2010) adopt a conceptual framework that stresses the importance of the intermediary levels when developing learning progressions. Using terminology such as anchor points, stepping stones, lever concepts, and linchpins, they describe instruction-assisted conceptual development that is based on learners' extant knowledge. Taking a narrower grade 3-5 perspective on the Learning Progression for Matter (LPM), the goal is to help learners bridge from lower to upper anchors by supporting a series of broad reconceptualizations. The stepping stones are intermediate states in the bridging processes of the knowledge network. Lever concepts are core concepts present in the lower anchor (e.g., weight) and are held to be important components for the targeted upper anchor concepts (e.g., mass, density). The lever concepts are salient in students' everyday thinking and are intimately related/connected to other ideas. The linchpins are seen as organizers to express the structural aspects and/or relations among concepts in the upper anchor. Linchpins then are tools that make it possible to re-conceptualize the lower anchor lever concepts. Therefore, these intermediary components in LPs that are targeting reconceptualizations operate as instruction assisted development.

For example, in the LP for matter (LPM) (Smith et al., 2010; Wiser et al., 2009), knowing that weight is an inherent property of matter and knowing that tiny visible things have weight or take up space are important stepping stones in elementary school science for developing more sophisticated understandings about matter and density. Weight, size, and material are seen as lever concepts for the development of the upper anchor concepts of volume, density, and matter. Measurement of lever concepts is an important component of the LPM that moves students from sensory experiences and a trust of their senses as a reliable information epistemology to mathematical analysis as an epistemology. Quantification of weight and object size helps children to re-conceptualize how weight changes or remains constant in tracing matter over time. The shift is from perception-centered thinking to model-mediated thinking and the development of quantitative reasoning and understanding of measurement (Smith et al, 2010). One of the linchpins in the LPM is the 'measure line,' which is a linear, quantified representation of measuring weight or volume. Wiser et al., used the measure line as an instructional intervention to help students record and represent/link the 'felt (hefted up) weight' with the 'scale (measured)

weight' to produce a weight line. Thus, the stepping stones, lever concepts, and linchpins were applied to the LPM as interventional instruction strategies to support reconceptualizations that progress students from the lower anchor at third grade to the upper anchor at fifth grade.

Once again, the emergent tradition for the teaching and learning sciences is to frame learning in contexts that merge content knowledge with skills, practices, and processes to generate *learning performances.* An undeniable trend in STEM (Science, Technology, Engineering, and Mathematics) education is that more and more contemporary science is being done at the boundaries of disciplines (e.g., Earth systems science, biophysics, geochemistry, bioengineering). Thus, we recognize now a connectedness in the practices of science that are not typically found in school classroom environments or the design of science curricula.

Many of the extant K-8 science curriculum programs have been found wanting in terms of the lean reasoning demands required of students (Ford, 2005; Hapgood et al., 2004; Metz, 1995; NRC, 2007a). What the research shows is that curricula addressing domain-general reasoning skills and surface-level knowledge dominate over curricula addressing core knowledge and domain-specific reasoning opportunities that meaningfully integrate knowledge. This situation, researchers claim, is partially due to a lack of consensus in curricula about what is most worth learning and to K-8 teachers' weak knowledge of science. The reasoning-lean curriculum approaches tend to (a) separate reasoning and learning into discrete lessons thus blurring and glossing over the salient themes and big ideas of science and thereby making American curricula "a mile wide and an inch deep" (Schmidt, McNight, & Raizen, 1997) and (b) present science topics, in the case of middle school textbooks, as unrelated items with little or no regard to relations among them (Keisdou & Roseman, 2002).

Ohlsson (1992) recognized some years ago that the focus on teaching scientific theories did not include using the theories; what was missing were cognitive processes involved with theory articulation and refinement. Ford (2005) in a study examining 3rd grade students' engagement with a kit-based unit on *Rocks and Minerals* found that the principal learning goals for the set of lessons was classification reasoning. Descriptive observational features of rocks and minerals were used to assign rocks to types (e.g., sedimentary, igneous, metamorphic) and to kinds (e.g., sandstone, siltstone, shale, limestone). Missing from the curriculum learning goals was any expectation for using information from rocks (e.g., larger grain size in sedimentary rocks implies higher energy water environments) and minerals (e.g., larger grain size in rocks implies a slower cooling) to tell a story about the rocks. Ford concludes that the lessons in the kit were impoverished and underestimated the known capabilities of children to engage in science.

Research on young children's learning demonstrates that children entering school are well equipped cognitively and socially to engage in theory and model building. The role of modeling natural phenomenon and then reasoning from those models has led Ford (2008), Herrenkhol and Guerra (1998), Lehrer and Schauble (2004, 2006), and Smith (2007), among others, to investigate ways to design classroom learning environments that promote students' theory and model building reasoning. Lehrer and Schauble (2006) report on a 10-year program of longitudinal research that examines planned instructional sequences across grades K-5. The focus is model-based reasoning and instruction in science and mathematics. Critical to the design of these learning environments is engagement in analogical mapping of students' representational systems and their emergent models to the natural world. Important instructional supports are coordinated around three forms of collective activity: (a) finding ways to help students understand and appropriate the process of scientific inquiry, (b) emphasizing the

development and use of varying forms of representations and inscriptions, and (c) capitalizing on the cyclical nature of modeling (p 381).

Sandoval (2003) has explored how high school students' epistemological ideas interact with conceptual understandings. Written explanations in the domain of natural selection were used as the dependent measure. Analyses showed students did seek causal accounts of data and were sensitive to causal coherence, but they failed to support key claims with explicit evidence critical to an explanation. Sandoval posits that while students have productive epistemic resources to bring to inquiry, there is a need to deepen the epistemic discourse around student-generated artifacts. The recommendation is to hold more frequent public classroom discourse focused on students' explanations. "Epistemically, such a discourse would focus on the coherence of groups' claims, and how any particular claim can be judged as warranted" (p. 46).

Sandoval (2005) argues that having a better understanding of how scientific knowledge is constructed makes one better at doing and learning science. The goal is to engage students in a set of practices that build models from patterns of evidence and that examine how what comes to count as evidence depends on careful observations and building arguments. Schauble, Glaser, Duschl, Shultz, and Johns (1995) found that students participating in sequenced inquiry lessons with explicit epistemic goals (e.g., evaluating causal explanations for the carrying capacity performance of designed boats) showed improved learning over students who simply enacted the investigations. They found that students' understanding of the purposes of experimentation made a difference. Other reports of research that have found positive learning effects for students working with and from evidence and seeing discourse and argumentation as a key feature of doing science include Kelly and Crawford (1997), Sandoval and Reiser (2004), Songer and Linn (1991), and Toth, Suthers, and Lesgold (2002).

Additional insights for the design of reflective classroom-discourse environments comes from research by Rosebery, Warren, and Conant (1992); Smith, Maclin, Houghton, and Hennessey (2000); van Zee and Minstrell (1997); and Herrenkohl and Guerra (1998). Rosebery et al.'s (1992) study spanned an entire school year, while Smith et al.'s (2000) followed a cohort of students for several years with the same teacher. Both studies used classroom practices that place a heavy emphasis on (a) requiring evidence for claims, (b) evaluating the fit of new ideas to data, (c) providing justifications for specific claims and (d) examining methods for generating data. Engle and Conant (2002) refer to such classroom discourse as "productive disciplinary engagement" when it is grounded in the disciplinary norms for both social and cognitive activity.

The research by van Zee and Minstrell (1997) shows the positive gains in learning that come about when the authority for classroom conversation shifts from the teacher to the students. Employing a technique they call the *reflective toss*, van Zee and Minstrell found that students become more active in the classroom discourse, with the positive consequence of making students' thinking more visible to both the teacher and the students themselves. Herrenkohl and Guerra (1998) examined the effect that guidelines for student audience members had on student engagement, that is, the effect scaffolding had on listening to others. The intellectual goals for students were (a) predicting and theorizing, (b) summarizing results, and (c) relating predictions, theories, and results. The audience role assignments were designed to correspond with the intellectual roles and they required students to check and critique classmates' work. Students were directed to develop a *question chart* that would support them in their intellectual roles (e.g., What questions could we ask when it is our job to check summaries of results?) Examples of students' questions are: *What helped you find your results? How did you get that? What were your results? What made that happen? Did your group agree on the results? Did you like what*

happened? Following the framework developed by Hatano and Inagaki (1991), Herrenhkohl and Guerra used the audience role procedures to engage students in asking clarification questions, challenging others' claims, and coordinating bits of knowledge. The focus on listening skills and audience roles helps to foster productive community discourse around students' *thinking in science*.

Summary and Future Directions

In conclusion, researchers studying science learning and STEM education are learning that with proper supports (e.g., instruction-assisted development, assessment for learning) and sequencing (e.g., immersion units and learning progressions) young children and adolescents are capable of complex reasoning and of engaging in sophisticated scientific critique and communication practices. The research reviewed here demonstrates that theory-building, modeling, and other forms of scientific reasoning are possible when learners are provided with multiple opportunities that sustain engagement with select scientific practices over time (e.g., predicting, observing, testing, measuring, counting, recording, collaborating, and communicating). When sustained engagement and instruction-assisted development occurs, the research shows that learners develop images of the nature of science and of scientific inquiry as an enterprise that is fundamentally a theory/model building and refining process. Viewing classrooms and other formal and informal learning environments as a scientific community, in which learners participate in scientific practices and discourse processes akin to professional communities in the sciences and engineering, is under studied. We need more research here.

The climate change education program being proposed here to link climate science and engineered systems is indeed complex. But such complexity provides affordances and hence can become an advantage when long-term educational efforts like learning progressions are adopted. The growth of knowledge (among scientists and engineers and among learners) advances through interactions within communities. Studies of science/engineering communities through case studies as proposed in the Phase 1 CCEP proposal can reveal and inform our understandings (1) of the cognitive, epistemic and social practices that occur and (2) of how to design and research hypothetical learning progressions on engineered systems and climate change.

Posing and refining questions; posing and refining hypotheses; posing and refining designs of engineered systems and climate studies; developing shared representations and models; considering alternatives; and providing feedback are but some of the interactive science and engineering practices with which climate science and engineered system engage. A research program that takes up the study of climate science and engineered systems represents a robust context for situating and studying science learning and teaching. The importance of research on developmental trajectories/progressions that examines learning and reasoning has been described. Much of this research, while informed by lab studies and cross-age interview data, must go further in order to establish a stronger empirical base. One aspect of going further is to study the pathways, trajectories, or progressions where learning occurs, which in the study of learning environments is where student learning is taking place. Another aspect of going further is to study how teachers are engaging in such new 'pathway' sequences for instructional units. That is, how does a teacher come to understand the alignments and coherence among curriculum-instruction-assessment that, in turn, frame instruction-assisted development? There needs to be more research about the design of tasks that make thinking visible and thus inform and guide instruction and learning. Here is where teacher feedback and teacher/peer mediation

can guide learners to increasingly higher levels of sophistication in understanding and using concepts in the implementation of practices.

Climate science and engineered system contexts in local, regional, as well as national domains represent an extremely rich and motivating forum for STEM education and STEM policy education. The research agenda will be complex given the new images we have of science, of capable young learners, of science and engineering participatory practices, and of the important role context plays in motivating the understanding and evaluation of climate science knowledge and engineered systems. But the rewards will be many as we develop richer understandings about the cultivation and motivation of K-16 STEM learning and teaching.

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