Standards for Science Education: Quantitative Reasoning and Modeling Concepts
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Introduction
Among the many challenges facing the transformation of K-16 science teaching and learning, is that of coordinating conceptual, epistemological and social competencies in disciplinary domains that are at one and the same time familiar and abstract to learners. When we consider the geosciences 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 the familiar phenomenon of our sense-based perceptions of the Earth and geoscience processes. From very early ages, however, we are also forced to confront phenomenon that do not present themselves in tangible 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 flood cycles 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 Earths’ surface and in outer space. 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.

When we consider these STEM discipline and computing 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 and can join in a workforce that is increasingly STEM and computationally driven. 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-16 students; one that will provide deeper and broader learning experiences. Deeper in the sense that understanding the complexity of scientific 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 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 chapter begins by presenting our framing of the relationships between systems thinking, model-based reasoning, and quantitative reasoning and how they are intertwined. Implications for current STEM and science education are examined. The next section examines recent developments regarding the run up to and the writing and dissemination of the Next
Generation Science Standards. 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 a ‘Learning Progressions and Model-Based Reasoning’ section that examines learning progression frameworks currently being developed, particularly around theory/model-building. Here technical language and frameworks being used in LP research is introduced. The intent is to demonstrate and argue that K-16 science education projects should adopt a LP perspective on developing curriculum, instruction, and assessment models.

Framing of Quantitative Reasoning and Model-Based Reasoning in Science Education

The interdisciplinary nature of science, as demonstrated by experts (e.g., Nersessian 2002, 2008), requires socially constructing knowledge about the interactions between various disciplines, in order to explain the physical, human, and created worlds. This means understanding the relationships of natural and human systems, their ever-changing nature, and how they influence and are influenced by other systems. To internalize this understanding means to internalize a systems thinking approach toward viewing and analyzing phenomena and processes.

In the context of Earth systems science, Assaraf and Orion (2005) define a system as, “…an entity that maintains its existence and functions as a whole through the interaction of its parts… [The] system attempts to maintain its stability through feedback. The interrelationships among the variables are connected by a cause and effect feedback loop, and consequently the status of one or more variables, affects the status of the other variables” (p. 519). When applying this definition to systems thinking, there becomes a need to evaluate phenomena not individually, but within a system and how changes to the phenomena affect other phenomena within the system and the system as a whole. For example, engaging in systems thinking means not studying the death of individual fish in a bay, but instead, studying the decreasing population of fish in the bay and how that impacts the bay ecosystem, as well as the human industry surrounding the bay.

Engaging in systems thinking involves being able to explain the system or components of a system under study and then predict the impacts the system will have on surrounding systems (Assaraf & Orion, 2005). To do this, a model is developed as an explanatory and predictive tool. It can be used to explain phenomena, collect data, predict outcomes (NRC, 2012), or persuade others (Lehrer & Schauble, 2006). We recognize that there are many different types of models and distinguishing between them is beyond the scope of this chapter. However, we embrace the idea that there is a “common element” of all models in their use as “external aids to reasoning – they are cognitive prostheses” (Duschl & Grandy, 2008, p. 21).

When scientists participate in the practices of science, they engage in model-based reasoning, which involves the development and use of varying forms of representations and the subsequent feedback and redesign of the model (Lehrer & Schauble, 2002, 2006) to develop theories about the world. We characterize model-based reasoning as the cognitive processes involved with developing model(s) – often varying mathematical entities based on data – to develop or redefine a theory. Duschl and Grandy (2008) argue that models “stand between data and theory…. and…models can be influenced by both data revisions and changes in theory commitments.” Here the notion is of a theory as “a family of models” and a model as “an abstract mathematical entity” (Duschl & Grandy, 2008; Giere, 1998, 1999). When engaging in model-based reasoning, scientists are engaging in the cognitive processes found within the intermediary realm be-
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between data and theory that involves the iterative process of analyzing data to then represent it in a way that either supports current theories or informs the development of new theories in order to explain aspects of a system. This type of reasoning is critical to the “doing” of science, since it incorporates analyses, explanations, and communication about systems.

Modeling involves the use of various different representations, some of which are quantitative in nature. As described in Taking Science to School: Learning and teaching science in grades K-8 (NRC, 2007), “Mathematics in all its forms is a symbol system that is fundamental to both expressing and understanding science. Often, expressing an idea mathematically results in noticing new patterns or relationships that otherwise would not be grasped” (p. 153). Both model-based reasoning and quantitative reasoning involve an iterative process of analyzing, modeling, communicating, evaluating, and redesigning models to explain scientific phenomena or processes.

Mayes, Peterson, and Bonilla (2013) define quantitative reasoning in science as “mathematics and statistics applied in real-life, authentic situations that impact an individual’s life as a constructive, concerned, and reflective citizen. [Quantitative reasoning] problems are context-dependent, interdisciplinary, and open-ended tasks that require critical thinking and the capacity to communicate a course of action.” The authors outline a framework for quantitative reasoning that includes 1) the quantification act, 2) quantitative literacy, 3) quantitative interpretation, and 4) quantitative modeling. When engaging in quantitative reasoning, a scientist would engage in a process that involves conceptualizing data quantitatively (e.g. quantification act), applying various mathematical skills to analyze and evaluate the data (e.g., quantitative literacy), interpret the results from the mathematical analysis of the data (e.g., quantitative literacy), and develop a quantitative model to represent the data (i.e. graph). (For a more detailed description of quantitative reasoning in mathematics, see Chapter 2 of this volume.) This characterization of quantitative reasoning in science represents how intertwined this practice is with model-based reasoning and how it is used to characterize components of a system.

We have developed a representation to characterize how we view the relationship between model-based reasoning and quantitative reasoning, within the context of systems thinking (see Figure 1).

![Figure 1: Relationship between Systems Thinking, Model-Based Reasoning, and Quantitative Reasoning](image-url)

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In our representation, quantitative reasoning and model-based reasoning are related, in that they involve analyzing, structuring, explaining, and representing data. When engaging in quantitative reasoning, one uses mathematical skills and concepts to analyze data of a natural or humanistic system and represent it as a model. The model is then used to make predictions, which leads to the collection and quantitative analysis of new data. This informs the redesign of the model, which then influences how that model is used to reason about the natural or humanistic systems. Both practices involve an iterative process in the development of models. Quantitative reasoning and model-based reasoning support a systems thinking habit of mind by explaining the mechanisms and interactions of systems in the natural and human world. For this reason, model-based reasoning and quantitative reasoning are within systems thinking.

Just as in science it is important to consider how phenomena within systems relate to one another, in science education it is important to consider how systems thinking, model-based reasoning, and quantitative reasoning are interrelated and what this means for students’ science learning. Though they are related to one another, each is just as important as the others for learning science. “Given the importance of science and engineering in the 21st century, students require a sense of contextual understanding with regard to scientific knowledge, how it is acquired and applied, and how science is connected through a series of concepts that help further our understanding of the world around us” (Achieve, Inc., 2013, Appendix A, p. 1).

**Earth Systems: An Example of 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 of geoscience inquiry methods and practices. 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 paved the way with geologists in the field getting up close and personal with rocks and structures. 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 a utilitarian orientation to the geosciences, we would argue, continues to dominate the curriculum of K-16 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 systems 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.

The ability to think systematically is an important habit of mind that supports not only the scientific background of the developing STEM workforce, but also future scientifically literate citizens. In a global society where future large-scale, scientifically based decisions will need to be made, it is important for the general populous to develop a systems thinking orientation toward the world. To do so, there is a need for understanding the explanatory and predic-
tive functions of models. Developing models that represent quantitative data requires applying mathematical tools to explain quantitative data and often leads to a quantitative model of the phenomena (e.g., graph) (Mayes et al., 2013). In current K-12 classrooms, science does not regularly connect to mathematics. It is important to remember, “science is a quantitative discipline, which means it is important for educators to ensure that students’ learning in science coheres well with their learning in mathematics” (Achieve, Inc., 2013, Front Matter, p. 10).

To develop a more scientifically literate society with a strong STEM workforce, there is a need to move away from classrooms teaching isolated facts, to a more integrated education system that values the need to support students’ understanding of how science is quantitative. Including and developing quantitative reasoning in the science classroom is an important step to developing students’ ability to analyze and model quantitative data to support an understanding of systems thinking.

National Science Education Reports

In addition to the changes the 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. The systems perspective is represented in four recent NRC reports – Taking Science to School (NRC, 2007), A Framework for K-12 Science Education (NRC, 2012a), Education for Life and Work (NRC, 2012c), and Discipline-Based Education Research (NRC, 2012b) – through their emphasis on deeper learning that connects the “what” of science with the “how” and “why.” Though the audience differs with each report, they all share in their push toward an integration of conceptual, epistemic, and social competencies within science education and beyond.

A Framework for K-12 Education and the Next Generation Science Standards

Recently, two influential National Research Council (NRC) reports have set a new course for U.S. science education. The two reports are Taking Science to School: Learning and teaching science in grades K-8 (NRC, 2007) and A Framework for K-12 Science Education: Practices, Crosscutting Concepts and Core Ideas (NRC, 2012a). The Framework is being used to guide the development of the Next Generation Science Standards, which is a States lead 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 conceptualized through climate sciences and engineered systems. One, is that science education should be coordinated around three dimensions - crosscutting concepts, core ideas, and practices (see Figure 2). Two, is that the practices should represent both science and en-

¹ Current State science standards 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.
Model-based reasoning and quantitative reasoning are particularly salient in the *Framework* with regard to the science and engineering practices. To engage in model-based reasoning, one needs to engage in all eight of the above-mentioned science and engineering practices, which is often an iterative process involving the design and re-design of the model to best explain all components in question. It involves ongoing communication with others and evaluation of the model (Lehrer & Schauble, 2006). Engaging in model-based reasoning is not only a process engaged in by scientists, but is advocated in the *Framework* to be foundational in science instruction for all students, whether interested in a STEM career or not. It supports depth to science learning and supports a systems thinking approach.

Since science is a quantitative field, it is imperative that quantitative reasoning be given a prominent place in the science curriculum. This is advocated within the *Framework* as practices two through five of the science and engineering practices (see Figure 2). Particularly this involves using mathematics to identify patterns, analyze and interpret data, model physical phenomena, and quantitatively communicate the structure and function of the phenomena (Mayes et al., 2013). Quantitative reasoning is represented as a component of model-based reasoning that bridges the divide between mathematics and science. Science is mathematical and should not be separated.

The push in the *Framework* for the integration of the science and engineering practices, crosscutting concepts, and core ideas is even more evident in the Next Generation Science Standards through the use of performance expectations. The performance expectations in the Next Generation Science Standards build off the explanation in the *Framework* that “…students cannot fully understand scientific and engineering ideas without engaging in the practices of in-
quity and the discourses by which such ideas are developed and refined. At the same time, they cannot learn or show competence in practices except in the context of scientific content” (NRC, 2012a, p. 218). To demonstrate this, the performance expectations in the Next Generation Science Standards will not just include what students will understand, as stated in previous standards (NRC, 1996), but will include what students will be able to do. For example, “5-ESS1-2: Represent data in graphical displays to reveal patterns of daily changes in length and direction of shadows, day and night, and the seasonal appearance of some stars in the night sky” (Achieve, Inc., 2013, p. 43). In this example, students are expected to use graphical representations (i.e., science practice) as a way to represent data about patterns in celestial movement (i.e. core idea).

The release of the Framework and forthcoming Next Generation Science Standards emphasized the need for science instruction that gives priority to depth over breadth:

Understanding the core ideas and engaging in the scientific and engineering practices helps to prepare students for broader understanding, and deeper levels of scientific and engineering investigation, later on – in high school, college, and beyond. One rationale for organizing content around core ideas comes from studies comparing experts and novices in any field. Experts understand the core principles and theoretical constructs of their field, and they use them to make sense of new information or tackle novel problems. Novices, in contrast, tend to hold disconnected and even contradictory bits of knowledge as isolated facts and struggle to find a way to organize and integrate them [24]. The assumption, then, is that helping students learn the core ideas through engaging in scientific and engineering practices will enable them to become less like novices and more like experts (NRC, 2012a, p. 25).

We also find the emphasis on deeper learning in two other documents recently released by the National Research Council: Education for Life and Work: Developing transferable knowledge and skills in the 21st century (NRC, 2012c) and Discipline-Based Education Research: Understanding and improving undergraduate science and engineering (NRC, 2012b). These two reports are unique in that they address different aspects of a students’ science education instruction; Education for Life and Work addresses learning of 21st century competencies (often referred to as 21st century skills) and their implications for deeper learning, while Discipline-Based Education Research (DBER) addresses postsecondary science education in the various science fields (e.g., physics, chemistry, earth science).

**Education for Life and Work**

The Education for Life and Work report identified the need for deeper learning, which involved incorporating 21st century competencies in classroom instruction. In doing so, they identified deeper learning as incorporating five types of knowledge:

- Facts, statements about the characteristics or relationships of elements in the universe;
- Concepts, which are categories, schemas, models, or principals;
- Procedures, or step-by-step processes;
- Strategies, general methods; and
- Beliefs about one’s own learning” (NRC, 2012c, p. 84; modified from Mayer, 2011).

This integration of the “types of knowledge” is similar to the integration emphasized in the Framework in that it incorporates all three dimensions, but with different terms and with the incorporation of beliefs about one’s own learning.
To develop this “deeper learning,” the *Education for Life and Work* report recommends the inclusion of “21st century competencies” – such as problem solving, critical thinking, collaboration – in instruction. The 21st century competencies include the integration of domain-specific knowledge and skills and support and extend science and engineering practices of the *Framework*. The competencies are divided into three categories: cognitive, intrapersonal, and interpersonal, but those most closely intertwined with quantitative reasoning and model-based reasoning are cognitive competencies, with some in interpersonal competencies (see Figure 3).

**Science and Engineering**

**Figure 3**: Overlap between various competencies from *Education for Life and Work* and science and engineering practices from the *Framework*

As identified in Figure 3, many of the competencies identified as having the strongest overlap between the science and engineering practices of the *Framework* and the competencies from *Education for Life and Work* support the development of model-based reasoning and quantitative reasoning. Most are cognitive competencies (e.g., critical thinking, information literacy, reasoning and argumentation, innovation). For example, nonroutine problem solving is similar to the focus of quantitative reasoning on ill-defined problems. This strong overlap between the 21st century competencies of the *Education for Life and Work* report and the science and engineering practices and crosscutting concepts of the Framework highlights the importance being placed on students learning the “doing” of science and not just facts. This importance is not just emphasized in the science education community, but in the informal education community, as demonstrated by this *Education for Life and Work* report.

The other consideration from this *Education for Life and Work* report is how it extends science learning. The other two 21st century competencies (intrapersonal and interpersonal) are not heavily represented in the overlap in Figure 3. Intrapersonal competencies are related to managing one’s behavior and emotions (e.g., flexibility initiative, appreciation for diversity, metacognition) and interpersonal competencies are related to expressing one’s ideas and interpreting and responding to others (e.g., communication skills, collaboration, responsibility,
Conflict resolution (NRC, 2012c). Some skills included in these two competencies are included in the three dimensions of the Framework, but others are not. Some interpersonal competencies, such as metacognition are known to be important to the learning of science (e.g., Magnusson & Palincsar, 2005) and should be included in the new science reform agenda. Within the interpersonal competencies, there should be clarification of the skills involved and how these relate to their application in the realm of science education.

**Discipline-Based Education Research**

The Discipline-Based Education Research (DBER) report extended the focus on integration of science practices and content into the area of postsecondary education. This report compiled research on teaching and learning in various science domains (physics, chemistry, biology, geosciences, astronomy, and engineering), which are conducted by scientists in those fields. The purpose was to highlight the need to change postsecondary science education to incorporate more research-based practices modified from fields such as cognitive psychology, educational and social psychology, psychometrics, and science education (NRC, 2012b). This report is an initial step for sharing research from these fields and highlighting future research agendas that will support the coherence of undergraduate students' science instruction and learning.

DBER scholars identified the lagging attention to integration of science and engineering practices, core ideas, and crosscutting concepts within postsecondary science instruction. The current science instruction focuses on teaching disconnected facts to undergraduate students with little to no consideration for integrating practices and crosscutting concepts such as systems thinking, model-based reasoning, and quantitative reasoning. An example of this disconnect arises from the geosciences community, which 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.* (National Oceanic and Atmospheric Administration, 2009)
- **Ocean Literacy**: The Essential Principles of Ocean Sciences K-12, *An ocean-oriented approach to teaching science standards.* (National Geographic Society, 2007)
- **Atmospheric Science Literacy**: Essential Principles and Fundamental Concepts of Atmospheric Science (National Oceanic and Atmospheric Administration, 2008).

The attention to Earth systems sciences is laudable and the involvement of geoscientists is commendable. What it has led to is a conflation and confusion of what actually counts as Big Ideas and Scientific Practices within the Geosciences community. The research from various NRC reports (e.g., NRC, 2002, 2005, 2006, 2007) 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 far too many fundamental concepts – e.g., 76 in *Earth Science Literacy* alignment and 44 in Ocean Literacy alignment. 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 where the concepts are developed, refined, used, and evaluated. Instead learning should parallel the science and engineering practices used by STEM practitioners.

Another area of concern 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 STEM education. Such sequencing and coherence of teaching and learning is a major orientation for STEM education research and development and comes under the headings 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 2), as well as the 21st-century competencies (see Figure 3). The important shift is away from an emphasis on merely knowing to an emphasis on using knowledge.

The lack of consideration within the above geoscience documents for the integration of the three dimensions parallels the limited integration of the three dimensions in science learning at the postsecondary level. The DBER report recognized this concern and highlighted current research within science disciplines around what it means to learn science in the disciplines (e.g., physics, geosciences) and best practices to support strong science instruction. This tended to focus on individual instructional practices that supported student learning and generally advocated for the integration of science and engineering practices within postsecondary science courses. Particularly, the focus of the report was on transferable learning, which involved learning across multiple classes and extended time periods (NRC, 2012b).

The DBER report and the Education for Life and Work report emphasized the importance of problem solving, spatial thinking, and use of representations in postsecondary science learning. This supports the development of model-based reasoning and quantitative reasoning in science with the intent of developing students’ systems thinking approach toward studying natural and human systems. Problem solving, as defined in the DBER report, referred to solving defined and ill-defined problems. For example, solving physics word problems (i.e., defined problems) compared to more ill-defined problems in chemistry. The processes used for problem solving involved applying all eight science and engineering practices from the Framework. Similarly, when defining representations and their qualities, the DBER report stated:

“Representations like diagrams, graphs, and mathematical equations are important in science and engineering because they facilitate communication, aid in the discovery of scientific facts, assist in problem solving, serve as memory aids, and generally function as tools for thinking” (NRC, 2012b, p. 98).

The definitions and processes required to engage in problem solving and use of representations as identified in the DBER report were similar to those characterized in the Framework. This supports the intention of the DBER community to increase the research and integration of science and engineering practices (and crosscutting concepts) with the learning of content ideas.

As a concern, a majority of the research included in the DBER report lacks attention to the integration of the three dimensions, three competencies, and deeper, transferable learning and, instead, focus on effects of individual instructional strategies. This demonstrates the “mile wide” nature of postsecondary education highlighted in the above geosciences documents. For this reason, the DBER report called for further research in postsecondary science education to focus on learning progressions that addressed the deeper learning of science core ideas and science and engineering practices across courses and between K-12 science education and post-

\(^2\) Research reviews on learning progressions in science, learning trajectories in mathematics, 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).
Learning Sciences and Science Learning: An Overview

In this section, a selected review of the literature is presented 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 TRESS (NRC, 2007) 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 taken from the learning sciences community and from the science studies community. Model-based reasoning becomes a critical component of this tripartite perspective, as it involves all three epistemic and social practices to characterize natural and human systems.

The learning sciences emerged from the earlier constructivist theories of learning and from the pioneering research in the cognitive sciences. Our deeper understanding of how 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, so-
ciological, 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 sci-
ence (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 scient-
ific 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 cul-
tural 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, 2007) rec-
commends 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; Subhrmanyam, Gelman, & Lfasse, 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) 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 struc-
tures 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 un-
derstandings of words as representing objects or actions are also indicative of emerging symbo-
ic capacities. Engagement with measurement and data representation can be introduced early
on as the PrePS² 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 measure-
ments, 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, Kim, & Schauble, 2007; 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 teacher 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 the 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 the acquisition of too many principles that are disconnected to practices and/or to use with other principles, then learning suffers.

Whether or not we choose 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, quantification, 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 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, as well as practices for 21st century skills, which are 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 bring 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 scientific 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’s involved in learning and doing science. Conversely, our understandings of what’s 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 discourse practices.

*Taking Science To School* (NRC, 2007) 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 data modeling, quantitative reasoning and conceptual understandings can, along with other science and engineering practices and the practices of 21st century skills, develop. Science and engineering practices are one of the three NRC Framework Dimensions (See Figure 1) and are an important component wherein the critique and communication discourse practices reside. Like the Core Ideas and Crosscutting concepts, the science and engineering practices and practices for 21st century skills require time to develop.

Thus, the recommendation in *TSTS* (NRC, 2007), in the NRC (2012a) *Framework* for science standards and in the Next Generation Science Standards, as well as in the NRC (2012c) *Education for Life and Work and Discipline-Based Education Research* (NRC, 2012b) reports 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 *TSTS* 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, 2007, 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, 2007).

To support the “exchange of knowledge” or transfer, deep understanding of a topic is necessary. LPs have the potential to characterize how that deeper understanding might develop across grade levels, for particular core ideas or science and engineering practices. This agenda for supporting extended deeper learning of 21st century competencies appears in Education for Life and Work, as well, stating:

“Developing deep knowledge of a domain such as that exhibited by experts, along with conditions for its use, takes time and focus and requires opportunities for practice with feedback” (NRC, 2012c, p. 80).

This emphasis on LPs, whether explicitly mentioned or not, is now filtering into many other aspects of education. There is now a need to consider how these different aspects of education (e.g., Earth systems science core idea, practice of mathematical and computational thinking, and problem solving) relate to one another and can be aligned to better support students’ development across the K-12 years.

Corcoran, Mosher, and Rogat (2009) convened several workshops of experts exploring LPs to look at two questions:

1. What promise might LPs have for improving instruction in schools?
2. 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, four features were found to characterize LPs (Corcoran, et al, 2009):

1. Targeting core and generative disciplinary understandings and practices that merge science content with science practices;
2. Lower and upper boundaries that describe entry assumptions and exiting expectations for knowing and doing;
3. Descriptions of LPs that inform progress levels or steps of achievement; and
4. 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 and 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 “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
Quantitative Reasoning and Modeling Concepts in Science Standards

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

Unfortunately, the NRC (2012b) report on Discipline-Based Education Research found that “very little research at the undergraduate level provides evidence of conceptual change over time as a result of instruction or other learning experiences” (p. 73). This is particularly disconcerting as many other fields (e.g., K-12 Science Education, Informal Education) are moving toward a more longitudinal perspective of learning. The discipline-based education research community needs to build from current science education research about teaching strategies that support science learning and develop LPs that extend across courses in each science discipline, as well as from K-12 science education into the postsecondary environment. With the educational focus shifting from K-12 to K-16, the “STEM pipeline” needs more research at the postsecondary level to support the continued and deeper learning of the various science disciplines.

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 proceed with the discipline-based education curriculum redesign agenda. Corcoran and Silander (2009) conducted a review that examined the effects of 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 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 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 of instruction-assisted development that, 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). The position is 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 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 the case of postsecondary across courses. This eliminates as LP research 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 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 engaging 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

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

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…the point is that the kinds of reasoning processes should aim to approximate those of a scientist.” (2008, p. 78).

The work of scientists and the practices emphasized in the laboratory setting provide a unique perspective with regard to the new science education agenda emphasizing integration across K-16 science instruction. “Well-designed laboratories can help students to develop competence with scientific practices such as experimental design; argumentation; formulation of scientific questions; and use of discipline-specific equipment such as pipettes, microscopes, and volumetric glassware” (NRC, 2012b, p. 130). The postsecondary laboratory provides a unique and important environment to support the learning of many science practices, including model-based reasoning and quantitative reasoning. The intent is to support deeper, transferable learning that can promote a systems thinking orientation toward the world.

Brickman, Gormally, Armstrong, and Hallar (2009) studied the effects of inquiry-based laboratory settings on undergraduate students’ science literacy skills. They found that students who received an inquiry-oriented laboratory instruction demonstrated increased science process skills, which emphasized the use of quantitative reasoning. This demonstrates the potential for laboratory experiences to support students’ understanding of what it means to “do” science.

With the new science agenda aiming to increase integration and coherence across science instruction in K-16 classrooms, the current and future students will be receiving a very different educational experience than what the current undergraduate students received during their K-12 years. The questions then become: How will the postsecondary science community adjust to meet the needs of these future undergraduate students? What does this mean for the current lecture-driven postsecondary science community? How can future DBER research begin changing the undergraduate environment to be more coherent and cross-curricular?

**Learning Progressions and Model-Based Reasoning**

Descriptions of learning progressions involve establishing a beginning point and an ending point that can span months, semesters, or years. *TSTS* (NRC, 2007) 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 makes this LP appeared 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) changes overtime in individuals’ 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 (NRC, 2007) represents upper anchors as the successive adoption of more accurate scientific understanding and increasing 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.

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 a process of iterative design based research implementations and refinements of the curriculum sequence researchers are working on reorganizing the intricate network of domain-specific concepts and doing so in the context of scientific decision-making.

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 held to be important components for the target upper anchor concepts (e.g., mass, density). The lever concepts are salient in students’ everyday thinking and 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 reconceptualize the lower anchor lever concepts. Therefore, these intermediary components in LPs targeting reconceptualizations operate as instruction assisted development.

For example, in the LP for matter (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 volume, density, and matter. Measurement of lever concepts is an important component of the LPM to move students from sensory experiences and a trust your senses as reliable information epistemology to mathematical analysis as an epistemology. Quantification of weight and object size helps children to reconceptualize 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.

The levels within a learning progression should also include understanding for and applicability of science practices. Gunckel, Covitt, Salinas, and Anderson (2012) developed a learning progression about water in socio-ecological systems that incorporated various elements of the 3 dimensions from the Framework. Each level was defined by the extent to which understanding of each factor was elaborated: 1) structures and systems, 2) scale, 3) scientific principles, 4) representations, and 5) dependency and human agency. A student was considered to represent a level 4 understanding and strong model-based reasoning when they demonstrated cohesive scientific understanding and applicability of each of the five factors. This required students to represent understanding of how to “[develop] and use models, [interpret] data, [construct] explanations, and [engage] in arguments from science” (p. 860).

Once again, the emergent tradition for teaching and learning science is to frame learning in contexts that merge content knowledge with skills, practices, and processes to generate learning performances (Krajcik et al., 2008). An undeniable trend in STEM (Science Technology Engineering 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, among others). 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, 2007). 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, they 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 (a) tend to separate reasoning and learning into discrete lessons thus blurring and glossing over the salient themes and big ideas of science thereby making American curricula “a mile wide and an inch deep” (Schmidt, McNight, & Raizen, 1997) and (b) in the case of middle school textbooks, tends to present science topics as unrelated items with little or no regard to relations among them (Keisidou & Roseman, 2002).

Ohlsson (1992) recognized some years ago that the focus on teaching scientific theories did not include using the theories; 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), Herrenkohl and Guerra (1998), Lehrer and Schauble (2004, 2006), 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 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).

When designing learning environments, students need support in engaging in argumentation using model-based reasoning. Herrenkohl, Palincsar, DeWater, and Kawasaki (1999) studied middle to upper elementary students’ abilities to engage in structured discussions about predictions and theory building in the context of sinking and floating objects. The students developed conceptual models of why some objects floated and others did not and then shared those conceptual models (i.e. theories) with their peers. The structured discussions allowed students to engage in scientific argumentation that involved critiquing their conceptual models and experiencing the cyclical nature of models as they refined them to better align with and predict data. They gained a deeper understanding of problem solving in science, which is an important cognitive competency that supports quantitative reasoning and model-based reasoning.

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 of stu-
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 come 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 that of Smith et al. (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) 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 student thinking more visible to both the teacher and the students themselves. Herrenkohl and Guerra (1998) examined the effect on student engagement of guidelines for students who constituted the audience, that is, the scaffolding was on listening to others. The intellectual goals for students were predicting and theorizing, summarizing results and relating predictions, theories, and results. The audience role assignments were designed to correspond with the intellectual roles and 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), Herrenkohl and Guerra used the audience role procedures to engage students in (a) asking clarification questions; (b) challenging others’ claims; and, (c) 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 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 systems thinking nature of science and of scientific inquiry as an enterprise that is fundamentally a model-based reasoning and refining process. Viewing classrooms and other formal and informal learning environments as a scientific community in which learners participate in science practices and discourse processes akin to professional communities in the sciences and engineering is under studied. We need more research here.
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.

The importance of research on developmental trajectories/progressions that examine learning and reasoning has been presented. 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; in the study of learning environments where student learning is taking place. This includes studying the progression of learning into the undergraduate science environment.

As we focus on a systems thinking approach to science with model-based reasoning and quantitative reasoning as tools to characterize components and processes within systems, we must consider how this new approach impacts the development of learning progressions. As advocated in the Framework, Education for Life and Work, and DBER reports, learning progressions should incorporate the three dimensions (core ideas, crosscutting concepts, and science and engineering practices), as well as three competencies and should span K-16 education. This emphasizes deeper learning with the use of minimal core ideas to develop a systemic understanding of those core ideas across years of learning.

The Next Generation Science Standards emphasizes this deeper learning by using an evidence centered design approach toward the integration of the three dimensions in the new performance expectations. Students are expected to demonstrate understanding of the core ideas by applying that understanding through the use of various science practices. This application represents the need for evidence to support understanding of the core science concepts. By applying their understanding, students are making their thinking visible for both themselves and their teachers. Teachers can then use this information to inform their instruction of how to support students in continued depth of science learning and how to apply that understanding to new ideas and the practices of science.

In contrast, the Climate Science literacy documents – The Essential Principles of Climate Science (NOAA, 2009), The Essential Principles of Ocean Sciences K-12 (NGS, 2007), The Big Ideas and Supporting Concepts of Earth Science (USGS, 2009), and Essential Principles and Fundamental Concepts of Atmospheric Science (NOAA, 2008) – represent the choice of breadth over depth in the science disciplines taught at the undergraduate level. This continued focus on learning discrete facts instead of a more systems thinking approach is highlighted in the DBER report as a concern for undergraduate science education. Learning at the undergraduate level is still represented by the ability to restate facts instead of how to apply the concepts when engaging in the doing of science. Undergraduate science education will need to reconceptualize how science is taught in the upcoming years, in order to continue the progression of learning from K-12 science education into the undergraduate courses and to help undergraduate students engage in the practices of science.

Another aspect of going further is to study how teachers are engaging in such new ‘pathway’ sequences of instructional units. That is, how does a teacher come to understand the alignments and coherence among curriculum-instruction-assessment that, in turn, inform and 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 guides learners to increasingly higher levels of sophistication in understanding concepts and using concepts in the implementation of practices. The research agenda highlighted in the various NRC reports will be complex given the new images we have of science, of capable young learners, of science and engineering participatory
practices, of 21st century competencies, and of the important role context plays in motivating the understanding and evaluation of 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.

References


Quantitative Reasoning and Modeling Concepts in Science Standards


