INTRODUCTION

In this chapter, we take up a review of the literature on science learning and teaching that is guided by the concomitant and ongoing developments in cognitive sciences and science studies begun during the second half of the 20th century. We have chosen to focus our review 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 context (e.g., conceptual, epistemological, and social), at different ages (e.g., preschool, K–8, secondary, adult) and in various learning environments (e.g., formal and informal).

The first topic we examine is research on the knowledge and skills that young children bring to school, the results of which are shaping how we think about the learning and teaching of science and the design of learning environments. The second topic looks at research on the role of adaptive instruction and instruction-assisted development that argues for an alignment of curriculum, instruction, and assessment to foster learning progressions. The third topic looks at research and theory on epistemic practices, cognition, and learning. The review of research in these three topic domains is preceded by brief overviews of important theoretical, research, and methodological areas that are contributing to the current initiatives within science learning: (1) learning theory in science education and (2) learning analytics.

LEARNING THEORY IN SCIENCE EDUCATION

There is a long and storied history of learning theory perspectives in science education. The most recent developments are presented in the Linn and Eylon (2006) science education chapter in the 2nd Edition of the Handbook of Educational Psychology. In developing an adequate picture of learning within a science education context, Linn and Eylon (2006) identify the contributions of developmental, sociocultural, cognitive, and constructivist theory and research. The picture that emerges is one in which there is not one best way to engage students in the learning of science but a need for a variety of principles that will engage all students in important aspects of
knowledge integration. Linn and Eylon (2006) identify four interrelated processes of knowledge integration that need to be addressed in science learning context: a) eliciting existing student ideas, b) introducing new normative ideas, c) developing criteria to evaluate the scientific ideas they encounter, and d) sorting out new and current ideas using appropriate criteria. Linn and Eylon (2006) suggest that most approaches to knowledge integration within science education contexts have focused on the initial two processes and ignored the final two. They propose a set of design patterns that focus on specific instructional sequences (e.g., construct and argument, collaborate) that, when implemented, are aimed at ensuring that all important aspects of knowledge integration are addressed during science instruction. Linn and Eylon (2006) indicate that future research needs to explore how these design patterns impact learning within domain specific science education contexts and to assess their value in ensuring knowledge integration.

Linn and Eylon (2006) indicate that, in contrast to earlier research on learning science (see Fraser & Tobin, 1998; Gabel, 1994; White & Tisher, 1986), a wider variety of influential learning contexts have been identified and research has begun to assess their influence. Research on science learning appears to be moving away from a focus on general principles of learning science to a focus on the psychological, social, and cultural factors that influence the development of domain specific science knowledge. New images of science coupled with new images of learning have, in rapid succession, decade after decade, led to a plethora of perspectives on precisely what the foundations of science education might be. Is it the epistemological framework of the scientific discipline? Is it the sociological contexts of the investigative communities? Is it the psychological mechanisms that govern thinking and reasoning? Or, is it the cultural contexts that shape what it is that is important to know and to do? Such epistemic, social, psychological, and cultural perspectives have spawned a wide array of frameworks, and debates, for conceptualizing science learning and teaching over the years. In parallel with the development of new frameworks and debates comes the development of research agendas and programs that are aimed to evaluate the contrasting frameworks and address the ensuing debates about the nature of effective science learning and related teaching (see Tobias & Duffy, 2009).

Consider, for example, the recent discussions and debates in *Educational Psychologist* around minimally guided instruction being less effective than direct-guided instruction for science learning. On one side of the debate are theorists and researchers who indicate that the nature of our cognitive architecture (i.e., our need to search through and retrieve an incredibly large number of schema in long-term memory paired with a limited capacity working memory) support the need to retrieve knowledge efficiently and to develop usable knowledge through a directive and guided approach to science instruction. The thesis is that cognitive architecture and working memory theory dictate that instruction should be direct and explicit (Kirschner, Sweller & Clark, 2006; Sweller, Kirschner, & Clark, 2007). In contrast, the other side of the debate focuses on the need for authenticity of learning context and the need to situate the development of relevant science knowledge and skills within social and collaborative contexts that parallel the contexts within which scientific knowledge is developed and modified (Hmelo-Silver, Chinn, & Duncan, 2007, Kuhn, 2007; Schmidt, Lyens, van Gog, & Paas, 2007). The focus of the latter approach is to engage the learner in activities that will encourage the construction of knowledge within authentic settings. Current discussion of and research on these two approaches have focused on issues surrounding the value of hands-on types of activities and its relation to the development of accurate
understandings, the importance of prior knowledge, and the nature of knowledge to be acquired when assessing the value of instructional strategies (Chi, 2009; Lorch et al., 2010; Mayer, 2009).

Although research continues to support the superiority of direct-guided instruction over minimally guided instruction (Alfieri, Brooks, Aldrich, & Tenenbaum, 2011; Klahr, Zimmerman & Jirout, 2011; Lorch et al., 2010), there is some evidence that minimally guided instruction can have a positive impact when it is highly scaffolded (Alfieri et al., 2011). Lorch et al. (2010) found that, when teaching the control of variables strategy (a core skill in scientific reasoning) to primary school students, combining explicit instruction with experimentation (i.e., minimally guided instruction) produced significantly better outcomes than experimentation alone. Interestingly, Lorch et al. (2010) were also able to document distinct effects of the two types of instruction. That is, explicit instruction improved students’ understanding of the need to control irrelevant variables, while experimentation improved students’ understanding of the need to vary the focal variable.

What one finds when looking at the two sides of the debate is a clear difference with respect to learning goals. The views differ as to the primary focus or intent of the instruction (e.g., to develop increased knowledge of science content and skill or to develop increased generic scientific process and method skills). Hence, it is not surprising that there is evidence on both sides that support the value of both a minimally guided approach as well as directive approach to the teaching of science knowledge and skills (Blumenfeld, Kempler, & Krajcik, 2006; Tobias & Duffy, 2009). Future research should be focused on identifying under what conditions each approach works best; that is, what contexts and contents are well suited for a minimally guided approach and which are well suited for directive approach. The previously discussed results from Lorch et al. (2010) have begun to address this issue and suggest that blending the two approaches may be most beneficial to enhancing students’ science learning and knowledge.

Next, consider, also from Educational Psychologist, the wide ranging discussions in response to Geary’s (2008) article on applying evolutionary psychology to education theory and practice. Geary (2008) makes an important distinction between primary core knowledge, which we have evolved to acquire, and secondary knowledge that is culturally sanctioned and taught in schools but which we have not evolved to acquire. An example of primary core knowledge is the biological causal device of vitalism; that is, bodily processes are meant to sustain life by taking in and exchanging vital force (e.g., a substance, energy or information; Inagaki & Hatano, 2006). An example of a secondary knowledge is the Arabic numeral system (Spelke, 2000). Geary (2008) suggests that although there has been much research on documenting the primary knowledge of young children (see later discussion), there is a need to identify how these primary core understandings influence the development of related secondary knowledge. The distinction between primary and secondary knowledge may have some value in furthering the discussion surrounding minimally versus direct-guided instruction. That is, minimally guided instruction may be most useful focused on the enhancement and support of the development of primary knowledge but be insufficient for the development of secondary knowledge. It may be appropriate to expect learners to construct their own understandings of everyday and primary knowledge with minimal guidance; however, the content and nature of formal education may be much more complex and require more guidance to construct accurate understandings (Alfieri et al., 2011; Chi, 2009; Geary, 2008; Mayer, 2009).
Relevant to, but not directly related to, this issue is the emerging perspective on learning progressions research (Corcoran, Mosher, & Rogat, 2009; Duncan & Hmelo-Silver, 2009). Learning progressions, discussed more thoroughly in a separate section, are strategically developed cycles of activities that aim to engage learners in successively more sophisticated ways of thinking about an idea that build on one another as the students move through an area or domain (cf. Smith, Wiser, Anderson, Krajcik, & Coppola, 2004).

Finally, consider the current conversations concerning overcoming the gap between research and practice in education (Gordon & O’Brien, 2006; Kim & Hannafin, 2011). Bereiter (2014) suggests that one of the primary purposes of the learning sciences is to address this gap. The main focus of design research is to investigate learning in authentic settings to address the research-practice gap and generate more generalizable knowledge about learning (Cobb, Confrey, diSessa, Lehrer, & Schaub, 2003; Collins, Joseph, & Bielaczyc, 2004; Design-Based Research Collective, 2003). Bereiter (2014) suggests that this approach has not realized the potential envisioned by those who engage in design based research and that a possible more fruitful approach to the theory-practice gap may lie in what he refers to as “principled practical knowledge” (PPK).

PPK is identified as knowledge whose primary purpose is practical guidance in order to develop clearer specification of the potential links between theory and practice and to suggest future avenues for better understanding how to connect theory and practice. PPK is said to consist of the characteristics of both practical knowledge and scientific theory in that it combines the know how with the know why. Its purpose is not to explain or predict, but is said to be explanatorily coherent and systematic, i.e., explanatory coherent practical knowledge.

As an example of the development and potential value of PPK, Bereiter (2014) discusses Scandova’s (2004) design research focused on the impact of conceptual and epistemic scaffolds on the development of students’ scientific inquiry skills. Through design research aimed at supporting student scientific inquiry, Scandova (2004) surmised that the integration of conceptual and epistemic scaffolds will best support students as they deal with specific problems in particular domains if it helps them understand the epistemic goals of their inquiry and provides conceptual guidance to support their problem solving activities. From this initial conjecture and integrating findings from various studies, Scandova (2004) developed the following theoretical conjecture: “epistemological ideas constrain the space of possible investigative strategies one might employ during inquiry to those that satisfy knowledge-making goals, but . . . such epistemological constraints function in relation to disciplinary knowledge” (p. 216). According to Bereiter (2014), this is an example of PPK, a coherent justification of practical knowledge (i.e., his original hypothesis about the importance of the integration of conceptual understanding and epistemic goals).

**Learning Analytics**

With the increased use of digital technology within educational settings and classrooms, we find ourselves with the ability to collect, share and represent immense amounts of data and information easily. Within a variety of current educational settings, there has been an increase in the gathering and analysis of large and multi-faced data sets. Given the immense amounts of data that are available through the use of digital technologies within education settings, the use of analytics has been employed to identify and discover meaningful patterns within the accumulated data. The analytics
include techniques such as predictive modeling, user profiling, adaptive learning, and social network analysis that are employed to help with the process of making important educational decision (Bienkowski, Feng, & Means, 2012). This has created new areas of research surrounding the use of these data and information to better understand institutions, learners, and instruction and to potentially create targeted support to enhance learning.

According to Peity, Hickey, and Bishop (2014), four learning analytic areas have grown out of the recent developments of digital technologies: a) academic/institutional analytics, b) learning analytics/educational data mining, c) learner analytics/personalization, and d) systematic instructional improvement. Academic/institutional analytics focuses the use of analytics to address institutional needs surrounding student access, admission, and services, and financial and administrative concerns of the academic institution. Learning analytics/educational data mining currently are viewed as converging; however, initially they arose from different concerns. Educational data mining began across many disciplines as a focus on searching large data sets to discover significant and potentially predictive patterns.

In contrast, learning analytics arose from the collection and analysis of data from learning management systems (LMSs) within higher education settings. Both of these approaches have converged within recent years to focus on “discovering what can be learned from large-scale fine-grained educational data, and how it can be used to promote learning” (Baker, 2013). Learner analytics and personalization is focused on collecting data related cognitive (e.g., processing) and non-cognitive (e.g., interests) characteristics and exploring how differences between learners affect their persistence and overall success. Finally, the area of systemic/instructional improvement has grown out the focus on data-driven decision making within the United States surrounding the federal mandates directing schools and teachers to regularly test students and use this data in their daily decision making process.

Although all these areas have the potential to contribute to our knowledge of the learning of science, the area that is particularly noteworthy, both in terms of its potential to impact science teaching and learning within classrooms and in terms of the beginnings of promising research programs, is the area of learning analytics. What is at the core of this area is a focus on the use of analytics to document and organize data from different contexts and settings in order to better understand how students learn and how educators and institutions can best support this process (Arnold, 2010, Baker & Yacef, 2009; Ferguson, 2012; Monroy, Rangel, & Whitaker, 2014; Suthers, Vatrapu, Medina, Joseph, & Dwyer, 2008). This emerging field is one of the fastest growing areas of research related to education and technology and has been fuelled by a substantial increase in data quantity, improved data formats, advances in computing, and increased sophistication of tools available for analytics (Baker & Siemens, 2014). As suggested, the focus and purpose of learning analytics is to effectively manage and employ data patterns to make recommendations for improving learning. Such decisions/actions could include identifying the need for intervention, personalizing support, or promoting self-regulation of learning (Brown, 2012)

One area that has benefited from the advent and use of learning analytics to capture and potentially better understand student learning of science concepts occurs within open ended learning environments (see, Kinnebrew, Biswas, Sulcer, & Taylor, 2013). Open-ended learning environments (OELEs) present students with learner-centered opportunities to take part in authentic and complex problem-solving tasks. With appropriate scaffolding, these opportunities are intended to support deeper
learning and the development of strategies that support future learning. Given the focus of *Next Generation Science Standards* on deep learning and the development of self-regulatory skills in science learners, OELEs seem well suited to encourage the deep learning of science concepts and skills within authentic settings.

A good example of the work being done in this area is occurring within the Teachable Agent Group at Vanderbilt University (Biswas, Leelawong, Schwartz, & Vye, 2005; Biswas, Segedy, & Leelawong, 2015; Blair, Schwartz, Biswas, & Leelawong, 2006; Kinnebrew, Loretz, & Biswas, 2013; Leelawong & Biswas, 2008; Segedy, Kinnebrew, & Biswas, 2015). They have developed computer based pedagogical agent software, called Betty’s Brain, that is designed to help middle school students learn about science (Leelawong & Biswas, 2008; Segedy, Kinnebrew, & Biswas, 2013). The software employs a model based approach to capture, measure, and assess the actions students take as they learn within this OELE through learning analytics. The model-based approach is based on the cognitive and metacognitive processes required to navigate and complete the complex learning tasks effectively (Segedy, Biswas, & Sulcer, 2014). Using the model, the system interprets students’ actions and behavior patterns as they relate to relevant cognitive and metacognitive processes, which then allows the software to offer up opportunities for adaptive scaffolds to help students more effectively learn the target science concepts and principles (Segedy et al., 2015).

Within Betty’s Brain, students teach the online agent (Betty) about science (e.g., ecosystems, thermoregulation) by building a concept map. The software also includes a mentor agent that can give guidance (but not answers) if required. The students use online resources to build the concept map, can ask for guidance from the mentor, and use feedback from the tests that Betty takes in order to modify their knowledge of target science concepts embedded in their developed concept maps. In addition, guidance and feedback can be embedded in the program that aims to develop the students’ self-regulatory skills by giving them advice on how to become a better learner and teacher within this context.

Within the context of ongoing research on Betty’s Brain, learning analytics have been employed in order to document a variety of online behaviors of the students (e.g., the amount of time spent viewing the library resources, making map edits, the best map score compared to an expert map). In addition, the analytics are able to generate information regarding students’ potential and actualized concept maps. Segedy et al., (2015) has employed coherence analysis in order to generate possible avenues of development given patterns of reviewing online resources and whether or not these avenues are realized in improved outcomes (i.e., better concept maps). Modeling the pattern of student behavior within this environment through coherence analysis is similar to mechanisms employed by online companies (e.g., Amazon) to identify possible products that users may be interested in given their online browsing patterns and behaviors.

Using the products of the learning analytics and the coherence analysis, Segedy et al. (2015) were able to employ exploratory clustering technique in order to identify and characterize common metacognitive actions and behavior profiles exhibited by students who were engaged in learning about human thermoregulation within Betty’s Brain. The analysis identified five distinct clusters, which were differentiated in terms of proportion of time reviewing resources, value of information reviewed to creating useful concept maps, time spent editing concept maps, and appropriate use of reviewed information and editing. For example, some clusters did not take full advantage of information reviewed or had difficulty identifying useful information while...
one cluster in particular focused mostly on useful information and used most of this information to edit their concept maps. Not surprisingly, students in the latter group performed significantly better than most other groups on the learning outcomes and nature of concept map (Segedy et al., 2015).

Although the results of the work of the Teachable Agent Group suggests important ways and avenues for employing learning analytics to help better understand learning within OELE, future research needs to focus on comparing the impact of Betty’s Brain with typical or conventional instruction. However, the combination of employing a model based approach within an authentic context with the ability to scaffold and assess on-going learning makes this work both current and relevant to the area of science learning as we move forward into the Next Generation era of science education.

CURRENT ISSUES AND TRENDS

The synthesis research report on science learning Taking Science to School (TSTS; NRC, 2007) 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 (cf. Keil, 1989; Subrhmamyam, Gelman, & Lafosse, 2002). The current research on cognitive development and reasoning in science also demonstrates that context matters in terms of content, learning environment, and learning goals (Atran, 2002; Koslowski & Thompson, 2002; Siegal, 2002). Embedding research on science learning within specific contexts has produced valuable insights into pathways or trajectories of learning in the disciplines (Catley, Reiser & Lehrer, 2005; Smith, Wiser, Anderson, Krajcik, & Coppola, 2004).

The following sections discuss three current issues or trends in theory and research on science learning in which there is much potential for identifying those factors that impact the learning of science as well as identifying gaps and possible future directions for expanding our knowledge of both learning and the learning of science. These three issues/trends are theory and research on (a) core knowledge and theory of mind, (b) learning progressions, and (c) epistemic cognition, thinking and practices.

Following the tenet of current cognitive psychological theory that it is easier to learn more about what one already knows, documenting what children come to school with is critically important. Charting the course of development of children’s conceptions and skills within core science areas is critically important to better understanding the nature of learning within science as well as the influence of specific contexts on their development. In addition, research on the impact of learning progressions on the acquisition of important science content continues to be an important area within science learning. Learning progressions are strategically developed cycles of instructional activities that aim to engage learners in successively more sophisticated ways of knowing and thinking about an idea that build on one another as the students moves through an area or domain (cf. Smith, Wiser, Anderson, Krajcik, & Coppola, 2004). The application of learning progressions within the area of science learning is a natural outgrowth of current views of learning that focus on the importance of epistemic and social influences on learning and development—addressing questions such as, “How did we come to know and develop scientific knowledge?” and “Why do we believe what we know (over alternatives)?” Relevant to this issue are the tensions that are created by different learning goals and outcomes and the best approach (i.e., a domain general
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approach versus a domain specific approach) by which to advance the specific learning goals and outcomes.

Core Knowledge: What Children Bring to School

The TSTS report (NRC, 2007) includes a research review on infant and young children’s cognitive capacities to address the guiding question: What do children bring to school? As documented in recent reviews of research on the capabilities of elementary school children, many of these children are able to think in abstract terms, make sense of their world through creating intuitive models or theories, and engage in experimentation to develop their ideas (Metz, 1995).

As part of a research program aimed at documenting preschool biological conceptions, Godfried and Gelman (2005) performed two studies to investigate children’s knowledge of internal parts within living and non-living things and their potential involvement in immanent causes for their behaviors. An example of an immanent cause is vital energy that is somehow generated by and emanates from a living thing. Previous research has suggested that preschool children endorse abstract immanent causes such as the living thing moved by itself; however, there is not much research to link conceptions of vital energy to causing movement and/or growth in preschool children.

In Study 1, the participants included preschool children in three separate age groups: 3-, 4-, and 5-year-olds. Each participant was asked questions about what was inside objects (i.e., animals, plants, and machines) presented in photos and were also asked to match photos of possible internal structures (e.g., bones, structure of blades of grass, circuit board) of these objects. The experimental materials consisted of 12 target photos of four animals (eland, tapir, pacarana, cavy), four plants (fern, moss, water lily, liverwort), and four machines (espresso maker, intercom, mini-TV, electric razor). The results showed that domain-specific knowledge of internal parts develops between ages 3 and 4. In Study 2, using similar materials as employed in Study 1, participants (4-year-olds, 8-year-olds, and adults) were asked yes or no questions about the relation between the specific internal parts, their insides, and the energy to either move, sit, or grow. Results showed that preschoolers did not endorse internal parts as causally responsible for familiar biological events (e.g., movement, growth). Preschoolers, however, were able to attribute an abstract cause (vital energy) for the movement of animals but not for machines. These latter results mirrored the results found for adults and older children.

Recent work by Setoh, Wu, Baillargeon, and Gelman, (2013) attempted to look at whether infants (8 months) would evidence behavior consistent with being aware of the biological concept of innards, self-propelling, and agency. They measured infants looking times due to specific manipulations of novel objects that the infants had identified as animals. In the familiarization phase of the experiment, Setoh et al. (2013) manipulated whether the novel objects (can or box) were self-propelled and agentive, or had animal like features (i.e., brown fur). The test phase consisted of manipulating the objects by either rotating or shaking them to test the infants’ expectations about the objects’ insides. Across all experiments, the infants’ patterns of looking times was consistent with them having expectations that objects classified as animals possess insides which appeared to be linked to their conception of animals possessing the critical attributes of self-propulsion and agency. Setoh et al. (2013) suggested that these expectations lay the groundwork for the development of more advanced biological knowledge.
In summary, the results suggest that children recognize domain-specific internal parts as early as age 4 but that their causal attributions are not yet linked to a detailed biological system (see also Slaughter, Jaakkola, & Carey, 1999; Zaitchick, Iqbal, & Carey, 2014). In addition, it is suggested the groundwork for the acquisition and development of this knowledge is present as early as 8 months (Setoh et al., 2013).

In addition, researchers are learning that young children are capable of complex reasoning when they are provided with multiple opportunities that sustain their engagement with select scientific practices over time like predicting, observing, testing, measuring, counting, recording, collaborating, and communicating (Carey, 2004; Denison, Bonawitz, Gopnik, & Griffiths, 2013; Gelman & Brenneman, 2004; Gopnik, 2012; Gopnik et al., 2004; Hapgood, Magnusson, & Palincsar, 2004; Metz, 2004; Spelke, 2000). Hapgood, Magnusson, and Palincsar (2004) documented how a targeted curriculum and pedagogy was used to create a learning community in which second grade children were engaged in investigations of scientific relations such as mass and speed. Within this learning community, the children were supported and held responsible for generating and testing their knowledge claims. In the course of instruction, the children and the teacher participated in two forms of investigation in which children were: a) directly exploring the physical world by manipulating variables in phenomena, making observations and measurements, and drawing conclusions about how the target variables are related (e.g., mass and momentum), and b) asking other children about their investigations and using text-based resources to compare to their own and other children’s interpretations of the target relations.

Teacher and student behaviors were documented by videotaping whole class, small group and individual writing activities. In addition, student generated text in response to classroom activities and tasks was collected. Finally, pretest and posttest were administered to assess student knowledge of the target science principles and concepts. From this evidence, Hapgood, Magnusson, and Palincsar (2004) found that the children in the class were able to use data as evidence to support their claims regarding the target relations regarding motion, evaluate approaches to assessing knowledge claims (e.g., experiments, discussion with other students, seek out relevant text), and use and understand multiple forms of representing data and claims (e.g., tables, diagrams, text). These practices required that the children engage in complex reasoning, which is integral to scientific inquiry.

By the time young children enter school, they already possess a surprising amount of capability to reason about the natural and social world. For example, they appear to be sensitive to a variety of high-level causal and relational patterns that are particularly useful for reasoning about living things (Inagaki & Hatano, 2002, 2006). In their experiments with 5-year-olds, Inagaki and Hatano (2002) have found that when instructed to compare animals and plants by analogy, these children were able to recognize similarities between animals and plants in terms of their reliance on food and water, respectively. That is, by using their rich knowledge of humans they could make analogical inferences about other living things.

Young children’s capabilities and knowledge is more robust for some areas than others, such as naïve biology (e.g., Inagaki & Hatano, 2006; Keil, 2003), naïve psychology (e.g., Wimmer & Perner, 1983), and naïve physics (e.g., Baillargeon, 2004). Underpinning these nascent understandings are several core knowledge systems that serve as the foundations upon which novel knowledge, skills, and beliefs are built (Spelke & Kinzler, 2007). These core knowledge systems appear to be innate and common to both human infants and some other primate animals and have been shown to represent
mechanical interactions between inanimate objects, goal-directed actions of animate objects, numerical relationships and ordering, and geometric relations and spatial layout (Spelke, 2004).

Recent theory and research looking at scientific thinking in young children suggests that children’s thinking and learning are quite similar to many aspects of learning and thinking in science (Gopnik, 2012; Gopnik & Wellman, 2012). Gopnik (2012) suggests that some of the patterns of thinking employed by young children mirror the different ways in which scientists also learn about their world: a) analyzing statistical patterns in the data, b) doing experiments, and c) learning from ideas and data of others.

Results from recent studies have indicated that infants and young children can detect and use statistical patterns to guide their behavior (Gweon & Shulz, 2011; Kushnir, Xu, & Wellman 2010; Xu & Garcia, 2008). Xu and Garcia (2008), using a looking time technique, found evidence that 8-month-olds were sensitive to statistical sampling patterns. Also, Kushnir et al. (2010) investigated whether young children (20 months old) would employ their sampling sensitivity to draw or infer alternative models to causal relations. They employed a choice paradigm that consisted of three phases. In the first phase, in the presence of the children, the experimenter took frogs out of a box of all frogs or a box that has some frogs in a box of mostly ducks. In the second phase, a different experimenter came in and gave the child a bowl of all ducks and a bowl of all frogs. In the final phase, the original experimenter returned and gestured toward the bowls to suggest that the child should give the experimenter something (i.e., a frog or a duck). Results showed that those children exposed to frogs being taken from an all frog box in phase one were equally likely to give the experimenter a frog or a duck within phase three. However, for those children who were exposed to frogs being taken from a mostly duck with a few frogs box in phase one, they most often gave the experimenter a frog in phase three. These results indicate that the children were sensitive to the statistical difference between the selection patterns and probability of choosing frogs and ducks given their experience within phase one.

Several studies suggest that even preverbal infants have a sense of mechanism and causality. In some of these studies (Baillargeon, 2004), infants were shown a toy resting at the bottom of a ramp. A cylinder is then rolled down the ramp, hitting the toy at the bottom. Using eye-tracking and eye-gazing methods, researchers have shown that infants as young as 8 months old correctly understand that a larger cylinder will move the toy farther away from the ramp. These infants can also understand that a barrier between the toy and the ramp would block the rolling cylinder and that the toy would not move. Thus, awareness of cause and effect, including the relation between magnitude of action and magnitude of effect, emerges very early on.

This early sense of cause and effect develops further during the preschool years. In several studies, Gopnick and colleagues (Gopnik & Sobel, 2000; Gopnik, Sobel, Sculz, & Glymour, 2001) showed young children a set up of multiple toy blocks, some of which were categorized as being “blickets,” and a contraption that can detect blickets (“blicket detector”). The young subjects were asked to identify the blicket blocks either by allowing them to experiment themselves or by having them observe a researcher place blocks (one or more at a time) on the blicket detector (without being told which are blinkets). Gopnik and her colleagues found that even two-year-olds could draw appropriate conclusions about causality and covariation by observing contingency patterns as blocks were placed on the detector by the researcher. Preschoolers in these studies were able to infer causality in complex situations involving multiple causes and probabilistic causality (Gopnick et al., 2001). More recent studies employing the
“blicket detector” experimental paradigm and a variant of this paradigm have replicated these results (Cook, Goodman, & Schulz, 2011; Legare, 2012). Recent research has also begun to attempt to identify those factors (e.g., state changes and negative outcomes) that may trigger children to engage in the type of causal reasoning described above (Legare, Schepp, & Gelman, 2014).

Reasoning about causal mechanisms is a core aspect of scientific practice and scientific explanations as exemplified by the second proficiency advocated by the TSTS report (i.e., generate and evaluate scientific evidence and explanations). The research reviewed in this chapter suggests that young children can reason about causal mechanisms even before formal schooling begins. Carefully planned and mediated instruction at the kindergarten and early grades can capitalize on these abilities and continue to develop them further (Gelman & Brenneman, 2004; Gelman & Lucariello, 2002).

The Preschool Pathways to Science (PrePS©), a science and mathematics program for pre-K children developed by Rochel Gelman and her colleagues (Gelman & Brenneman, 2004), is an example of a theory-based curriculum that builds on young learners’ emerging scientific understanding. In this program, the teachers introduce the language and ideas of observe, predict, and check early on in the year (during separate circle time sessions). Children then use their five senses to observe phenomena and objects such as an apple while the teacher records these observations on a publicly displayed chart. Using prior knowledge, children then predict what they cannot observe—what is inside the apple—and their ideas are recorded using drawings and labels. By cutting the apple, and examining the inside, children can then check their recorded predictions against the available data. The practices of observe, predict, and check are repeatedly used throughout the year and serve as a framework for thinking and talking about the natural world in scientific ways.

The PrePS© curriculum takes place over multiple months and is centered on core concepts, or big ideas, in domains that young children already have some substantive experience with and thus already possess some relevant knowledge about (such as insides and outsides of objects, form and function, systems and interactions). Over an extended period, young children engage with different experiences, encompassing different topics that are related to the core concepts. Similar understandings are not present when curricula cover multiple disconnected topics over short amounts of time (Winnett, Rockwell, Sherwood, & Williams, 1996).

Ongoing research suggests that the PrePS© curriculum is having a positive impact on pre-school children’s development of science knowledge (Gelman & Brenneman, 2013; Gelman, Brenneman, Macdonald, & Román, 2010). For example, children who are given repeated opportunities to run simple experiments in different scientific domains (e.g., sprouting seeds, insulating properties of different materials) are more likely to generate simple controlled tests when given novel problems. Although the initial results of the implementation of this curriculum are encouraging, there is a need to perform independent assessments that compare the value and impact of the PrePS© curriculum with other preschool approaches and curriculum.

Along with an emergent understanding of physical mechanism and causal interactions, infants and young children have knowledge of social interactions (Spelke & Kinzler, 2007) that develops into a theory of mind later in childhood (Ding, Wellman, Wang, Fu, & Lee, 2015; Perner, Leekam & Wimmer, 1987; Wellman, 1990, 2014). Infants are very much aware of differences between animate and inanimate objects. They assume different qualities and attribute different interpretations to the actions of people and other organisms as opposed to inanimate objects (Spelke, Phillips,
Woodward, 1995). Infants interpret human actions as goal-directed, reciprocal, and contingent (Spelke & Kinzler, 2007). For example, 12-month-old infants will follow the “gaze” of an object, if the object had earlier responded to the vocalizations of the infant and thus is assumed to be animate (Johnson, Slaughter, & Caret, 1998). While surprised if shown two cylinders acting on each other at a distance, infants are not surprised to see people acting on each other at a distance (Spelke et al., 1995). At infancy, the stage is set for the development of a more sophisticated theory of mind during the preschool years.

Before the age of 3, most preschoolers assume that others have the same thoughts and knowledge as they do. At this stage they are unaware that other individuals possess minds that are different from their own. A theory of mind, the idea that others may think and believe differently, emerges around the age of 3 and at this point preschoolers are able to understand that others may have false beliefs—that is, believe something that is at odds with reality (or at least the child’s perception of reality). The notion of false belief is tested through the Sally-Anne task (Wimmer & Perner, 1983) in which a child is shown a doll, Sally, placing an object in a certain place (marble in basket); the doll is then removed and another doll, Anne, moves the object to a new location. The child is asked where the marble is, and to predict where Sally will look for the marble. Children who possess a notion of false belief will correctly predict that Sally will search in the old location even though the child knows the sought after object is not there. By the age of 5, most preschoolers are aware that others may have different beliefs and ideas and that these can be at odds with reality (Wimmer & Perner, 1983).

An individual’s theory of mind is a critical precursor to several aspects of their scientific reasoning. A theory of mind affords the understanding that knowledge can be subjective and people may have different interpretations of natural phenomena. This is relevant in grasping the revisionary nature of scientific knowledge and the existence of alternative models for explaining a phenomenon. It follows that in order to engage in scientific argumentation (a core practice we would like students to master), children need to have a theory of mind and notion of false belief that allows them to assume that explanations vary and that explanations may be more or less accurate depictions of the phenomenon in question. There is clear need to investigate the link between the development of children’s theory of mind and their ability to benefit from engaging in modeling phenomena and arguing about alternative models and theories (NRC, 2007). It also follows that if learning environments do not present science as a theory-building or model-building enterprise with a specialized way of talking, writing, and representing ideas, then these innate abilities may fade away (Gopnik, 1996).

Gopnik and Wellman (2012) indicate that recent work within the area of theory of mind has identified new and significant areas of the dynamics of theory change. First, theory formation both in science and in childhood is significantly influenced by probability and statistical information. Second, research and theory has identified the power of informal experimentation for both adults and children. Children, in particular, can learn from their own interactions with objects within the world as they are exploring their environment (e.g., exploratory play) as well as learn from observing others both in educational and non-educational settings. Finally, theory change is not seen to be an all or none phenomenon. Different world views or hypotheses can be slightly changed or moderated such that multiple views and hypotheses can be maintained but with different likelihoods. This change process can occur through a series of steps gradually as they change their preferential weights across their different conceptions. Given the central role that beliefs related to causation play within the theory of
mind and the inherent statistical and probabilistic nature of causation, Gopnik and Wellman (2012) suggest that the probabilistic models can help us better understand what might be responsible for what children know (i.e., intuitive theories) and when they come to know it.

Another area of recent development and research within theory of mind has focused on the role of executive function (EF) on the development or expression of the theory of mind (Barrouillet, 2015; Benson, Sabbagh, Carlson, & Zelazo, 2013; Carey, Zaitchik, & Bascandziev, 2015). Executive function is seen to consist of a suite of cognitive functions that underlie planning, cognitive control, self-control, and sustained attention (Diamond, 2013). Results of confirmatory factor analysis have identified three basic EF mechanisms: a) working memory (storing and reorganizing information during on-line processing), b) inhibition (reducing activation of competing responses/information, and c) setshifting (selectively focusing on relevant information: Miyake & Friedman, 2012; Miyake, Friedman, Emerson, Witzki, Howerter, & Wager, 2000). There is evidence that EF and success in attributing a false belief (i.e., seen as an indication of the development of a theory of mind) are significantly correlated (Devine & Hughes, 2014). However, the results of research on infants and toddlers have also found evidence of their success on the false belief task (Onishi & Baillargeon, 2005). In addition, it is unclear whether EF’s role is one in which it allows for the cognitive context for the expression of theory of mind or is one in which it is has an important role in the construction of the theory of mind (Carey, Zaitchik, & Bascandziev, 2015). These are important questions to be addressed as we further develop the theory of mind and its relation to EF.

In addition to the potential importance of EF on the expression or development of a theory of mind, there is also research that suggests that EF is related to the development of an early developing intuitive theory important to science education, vitalist biology (Zaitchik, Iqbal, & Carey, 2014). These researchers were able to find a significant relationship between performance on an aggregate measure of EF and an aggregate measure of critical concepts of vitalist biology in 5 to 7 year olds.

In summary, the cognitive functions that underlie EF appear to be important contributors or constraints to the development of a theory of mind and an intuitive science theory. In looking at the further development of a theory of mind and instructional interventions aimed at the helping students acquire target scientific theories and knowledge, it would be important to consider and assess the impact of EF on relevant outcomes.

Let us now turn to children’s capacities for representation and the ways in which this practice can also serve as a foundation for model building in science. In many respects, children’s engagements in pretend play, in which one object stands in for another (a spoon for a rocket), are 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, 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 suggests 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, 2006). Lehrer and Schauble (2004) investigated the development of student understanding of natural variation through learning and reasoning about the statistical concept of distribution in a data-modeling context within authentic learning tasks. The focus of the research was to document the learning of students’ understanding of variation when the students are exposed to good but not extraordinary instructional experiences. In order to facilitate fifth-grade students’ understanding of variation, students engaged in a series of activities focused on taking responsibility for the growing of batches of native plants and attempting to find out how the plants would change over time and would be influenced by different growth conditions. Over a two month period, students’ reasoning related to and understanding of the concept of distribution and natural variation significantly improved through their 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 the simple statistical qualities of data, as well as the value of different types of representations for highlighting different features of data (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. Whether or not we choose to capitalize on children’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.

**Learning Progressions and Pathways**

In the introduction to a *Journal of Research in Science Teaching* special issue on Learning Progressions, Duncan and Hmelo-Silver (2009) reminded readers that learning progressions (or LPs) by their very nature are hypothetical; they are conjectural models of learning over time that need to be empirically validated. There is some consensus (Corcoran, Mosher & Rogat, 2009) that four features characterize LPs:

1. Targeting core and generative disciplinary understandings and practices that merge science content with science practices;
2. Having lower and upper boundaries that describe entry assumptions and exiting expectations for knowing and doing;
3. Including descriptions of LPs that inform progress levels or steps of achievement; and
4. Containing purposeful curriculum and instruction that mediates targeted student outcomes.

The recommendation for LPs represents a shift in emphasis 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. The emphasis on how and why reflects the *Taking Science To School* (NRC, 2007) recommendation that science learning needs to be strongly grounded in the use and consideration of evidence. This, in turn, leads to the recommendation that science learning be connected through longer sequences of instruction (e.g., immersion units; LPs) that function vertically across and horizontally within months and years of instruction. The rationale is to facilitate the learning of core science knowledge and practices that are critical for development of scientific knowledge and of the reasoning inherent in the four strands of proficiency. Developing rich, conceptual knowledge takes time and requires instructional support via sound assessment practices. The content of the LPs is the core conceptual knowledge as well as the epistemic practices (e.g., science talk and argumentation) and social practices (e.g., critique, communication and representation) that characterize a domain of scientific inquiry.

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, 2008, 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 National Research Council reports (1999, 2001, 2007). The emerging notion is for LPs at the K–8 grades to be built around the most generative and core ideas that are central to the discipline of science and that support students’ science learning. Additionally, the core ideas should be accessible to students in kindergarten and have the potential for sustained exploration across K–8 (NRC, 2007).

An examination of school curriculum, as stated above, reveals disconnected and isolated units of instruction to be the norm in K–8 science education (NRC, 2007). An examination of the growth of scientific knowledge as provided by longitudinal studies around LPs (Corcoran, Moser, & Rogat, 2009) and by science studies scholars (Nersessian, 2008) can provide some helpful insights on how to precede with the redesign agenda.

Corcoran and Silander (2009) conducted a review that examined the effects on high school student learning of instructional strategies. 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 monitor how students vary in what they are learning and adapt their instruction in response to students’ progress and needs was found to be a strong factor that supports student learning.

We believe . . . adaptive instruction is essential as it has the greatest potential for improving the efficacy of instruction . . . Admittedly, the evidence supporting the
effectiveness of adaptive instruction is weak at this point, but the theoretical argument is persuasive, and we believe adaptive instruction can be combined with student teaming, discussion methods, and even project-based learning to create more powerful pedagogies.

Corcoran and Silander (2009, p. 177)

One promising context for adaptive instruction is LPs. The Corcoran, Moser, and Rogat (2009) synthesis report is of several workshops that convened a group 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. 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 hypotheses represent pathways of learning that are based on research of students’ progress, like the well research learning pathway on matter and the atomic molecular theory (Smith, Wiser, Anderson & Krajcik, 2006; Smith, Carey & Wiser, 1985). The extant alternative is the selection of topics and sequences based on disciplinary experts logical analysis of content domains and teachers’ personal experiences as found in the American Association for the Advancement of Science (2001) Atlas of Science Literacy and in the scope and sequence frameworks common in school districts.

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 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.

Corcoran et al. (2009) also caution that while some promising efforts exist in select science domains and practices, the work is just beginning to produce valid and reliable evidence on the usefulness of progressions. A larger issue concerns whether progressions around core ideas and scientific practices are a potential alternative to standards. As we contemplate LPs as an approach to the organization and alignment of science learning, Schauble (2008) cautions that while we certainly want to answer the question ‘Where does reasoning and learning come from?’ we must also ask ‘Where is reasoning going?’ and ‘What conditions support productive change?’

Answers to the first question help us better understand the foundation on which further development can build. Answers to the second provide a sense of developmental trajectory, or more likely, trajectories. What characteristic changes are coming up? What pathways of change are usually observed? And answers to the third question focus on how those changes can get supported in a productive way.

(p. 51)
Two LPs research projects, one by Metz and one by Lehrer and Schabule, provide insights on how instruction-assisted development can inform adaptive instruction strategies. Metz (2008) reports on two curriculum-based studies with first graders; one in botany research on plant growth and one in animal behavior on crickets. The first-grade students’ engagements in knowledge-building practices are based on curricula scaffolded around seven interrelated features that support engagement in science practices: (a) immersion in strategically selected scientific domains; (b) centrality of big ideas in the practices; (c) entwining of content and process; (d) centrality of curiosity as a drive for doing science; (e) discovery and explanation as top level goals; (f) challenge of making sense of the ill-structured; and (g) the social nature of scientific knowledge-building practices. The initial versions of the curricula that demonstrated that children can design investigations around researchable questions and cope with uncertainty were designed and used successfully across several elementary grade levels (Metz, 2004). The first-grade vignettes draw from beginning, mid-point, and end of curriculum reports on the ways the deepening of knowledge supports thinking and contributes to increased accountability.

Another example of a study of instruction-assisted development is that by Lehrer, Schauble, and Lucas (2008). They engaged sixth-grade students in school year long pond studies. A part of the instruction had students design and build models of ponds in gallon jars. This provided a basis for studying questions the students had about the ponds. Lehrer et al. report that unintended outcomes like algae blooms and bacteria colonies afforded opportunities to examine how ecosystems function. Subsequent efforts to model the pond ecologies were supported by weekly research meetings. Here students would exchange ideas and discuss relations between evidence and explanations. The struggles students had with the material design of the jar-ponds to engage in inquiry were found by the researchers to foster a pedagogy of inquiry. End of year interviews with students were conducted to assess understandings about ecology and research design and beliefs about epistemology of inquiry. To get at views about the nature of inquiry, interviewers asked students to contrast the extended inquiry on ponds with kit-based science. The researchers found that the weekly research meetings were a major influence on students’ views about the nature of inquiry. Also, students reported that the repeated efforts and struggles to make the jar-ponds work was preferred over the clearer outcomes found in kits. Such a finding has important implications for research on motivating students to engage in science and build identities in science (Blumenfeld, Rogat, & Krajcik, 2006). Another finding from the pond study challenges current research findings on teaching and learning images about the nature of science and on epistemic cognition. Namely, the absolutist views (Driver, Leach, Millar & Scott, 1996; Lederman, 1992) students and teachers have about the nature of science and the absence of model-based views of science among learners do not develop when instruction-assisted inquiry is sustained. Within the right investigative context, students can develop more sophisticated views about the nature of science.

The content of LPS, core ideas and practices, can also be informed by science studies research. 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, and 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.

Lehrer and Schauble (2006) report that getting students to engage in resemblance representation tasks is an entrée to modeling. Lehrer and Schauble (2006, 2004) maintain that with instruction-assisted inquiry, modeling and reasoning as scientific practices can support a) sustained engagement with epistemic and social practices, and b) the construction of mathematical representational forms that afford quantification and investigation of relations among quantities. These instruction-assisted-development teaching sequences have students using and learning from data modeling, bridging mathematics and science, engaging in inquiry studies and using emergent representational forms.

The Lehrer, Schauble, and Lucas (2008), Metz (2008), and Nersessian (2008) results, along with research results from Carey and Smith (1993), Smith, Machlin, Houghton, and Hennessey (2000), Sandoval (2005) and Ford (2008), show that sustained engagements in instructional assisted inquiry do indeed affect views about the nature of science. Thus, this research challenges recommendations that a) the nature of science should be explicitly taught during lab lessons (Akerson, Adb-El-Khalick, & Lederman, 2000) and b) that such teaching should focus on a common, agreed upon set of features about the nature of science (McComas & Olsson, 1998). Finally, the research on extended instruction-assisted inquiry challenges the justified true belief image of science knowledge held by researchers studying epistemic cognition (Greene, Azevedo, & Torney-Purta, 2008; Murphy, Alexander, Greene, & Edwards, 2007). Here the research focus is on conceptual learning only, with no considerations for epistemic practices and nature of science views as learning goals.

**Epistemic Practices and Cognition**

The relevance of epistemic practices and epistemic cognition for science education is a growing topic of interest among science education researchers and educational psychologists. The inclusion of science studies research as frameworks for science learning (Duschl, 2008; Ford & Forman, 2006; NRC, 2007; Jimenez-Aleixandre & Crujeiras, in press; Manz, 2014) has given rise to a focus on science practices, in general, and epistemic practices, in particular. Concomitant developments regarding epistemic beliefs, values, and cognition have taken place in educational psychology (Greene, Sandoval, & Braten, 2016) but with a more domain-general stance regarding learning, thinking, and reasoning in terms of justified true beliefs with little or no consideration for science practices.
According to Elby, Macrander and Hammer (2016) the stage-like progressions assumed in the early work of personal epistemology persist in that epistemological progress moves from naive to sophisticated stages or beliefs within multiple dimensions. However, Elby et al. (2016) maintain that most current research reflects the assumption that epistemological views, when expressed in a science context (e.g., study of motion physics), can be construed as depictions about science in general as opposed to being domain-independent epistemological views.

Recent policy documents (NGSS, 2013; NRC, 2007, 2012) place scientific practices at the center of science teaching and argue for incorporating epistemic practices into instruction. There is, however, a diversity of approaches related to theoretical and educational aspects of epistemic practices. From theoretically oriented perspectives, epistemic cognition and practices are characterized in diverse ways, and have a range of meanings. Such diversity of thinking is evident in the *Handbook of Epistemic Cognition* (Greene, Sandoval, & Braten, 2016) and is taken up by the editors in the introductory chapter of that volume.

Some scholars (Hofer & Bendixen, 2012; Sinatra & Chinn, 2012) lament the disparate, and sometimes contradictory, terminology in the field. They feel it leads to conceptual confusion among researchers and practitioners alike, and that it erects walls between scholarly disciplines that otherwise share interest in the phenomenon of epistemic cognition. The decision to differentiate epistemic cognition, practices, and the like from standard (i.e., non-epistemic) cognition, judgments, and such suggests that researchers maintain that people’s thinking, actions, and goals differ when the focus is on building and refining knowledge.

Cognitive, historical, sociological, and anthropological studies of individuals working in knowledge building contexts reveals that the bulk of knowledge seeking activities in science are not about final theory acceptance, but rather activities targeting improvement and refinement of theories and models (Duschl & Grandy, 2008). 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) 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.

The proper perspective(s) between epistemology and science education are fraught with controversy, as well. An analysis of epistemic practices draws from several interconnected bodies of literature:

- Educational psychology and learning sciences (Barzilai & Zohar, 2014; Chinn, Buckland & Samarakunigavan, 2011; Hofer & Pintrich, 1997; Kuhn, Cheney, & Weinstock, 2000; Sandoval, 2005, 2014),
- Philosophy of science and epistemology (Longino, 1990, 2015; Pickering, 1995; Siegel, 1989, 2014), and

Thus, not surprisingly, there are differences of opinion. For Siegel (2014), mastering scientific practices is essentially psychological, pedagogical or social-scientific rather than philosophical, and so calling it “epistemological” is misleading. Siegel argues that the proper place of epistemology in science education is in the characterization of the
nature of science (NOS), how should NOS be taught, and what contributions to its understanding might be made by engaging students in scientific inquiry. But here, too, there are differences of opinion. Elby, Macrander, and Hammer (2016) maintain that science education researchers focus on epistemology largely for two reasons:

- Understanding the epistemic nature of science is an educational goal in itself, and
- Epistemic cognition connects to productive approaches to learning science concepts and practices.

With respect to NOS learning goals, there are also differences of opinion. One recent debate is about whether conceptions of NOS are best learned through explicit instruction of the features of science (e.g., scientific knowledge is tentative; scientists are creative; there is a distinction between theory and law; Abd-El-Khalick & Lederman, 2000; Osborne, 2014) or by immersing students in scientific inquiry (Sandoval, 2005) or practices (Duschl & Grandy, 2013). Sandoval, in particular, calls for the study of practical epistemologies (in situ epistemic cognition) to advance our understanding of how to promote NOS. Duschl and Grandy advocate focusing on the emergence of evidence from measurements and observations and then how evidence is used in building and refining explanatory models and mechanisms.

One influential characterization of epistemic practices is that by Kelly where he defines epistemic practices as “the specific ways members of a community propose, justify, evaluate, and legitimize knowledge claims within a disciplinary framework” (2008; p. 99). Kelly describes them as social practices, patterned sets of actions, performed by members of a group based on common purposes, with shared cultural values, tools and meanings. In his Handbook of Epistemic Cognition chapter that focuses on methodology, Kelly (2016) conceptualizes epistemic cognition as a practice, and epistemic practices as accounts for what counts as knowledge. Importantly for Kelly, epistemic practices are constructed in social interactions that include interactionally accomplished understandings of knowing. Kelly has found coding classroom discourse for such interactions very helpful in characterizing students’ learning, and he coordinates discourse analyses around four epistemic practice principles:

1. **Epistemic practices are interactional.** Engaging in social practices defines what counts as knowing and knowledge,
2. **Epistemic practices are contextual.** Knowledge is constructed through specific processes with variations across disciplines and ways of knowing.
3. **Epistemic practices are intertextual.** Discourse processes make use of and reference to previous discourse, both spoken and written texts, including the various signs and symbols characteristic of disciplinary knowledge, and are thus intertextual.
4. **Epistemic practices are consequential.** Ways of creating, representing, evaluating, and legitimizing knowledge have consequences for what and whose knowledge counts.

The emphasis on epistemic practices in science education is grounded in an approach that views science as consisting of a set of scientific practices (Osborne, 2014). Consequently science education needs to include “explaining how we know what we know or why we believe what we do” (Osborne, p. 580), for doing so will contribute to a
commitment to evidence as the epistemic basis of beliefs. Osborne considers that this commitment promotes rationality and critical thinking and is one of science’s major contributions to contemporary culture.

Longino (2015) draws a stark distinction between theory-centric and practice-centric approaches in philosophy of science that is useful for thinking about epistemic cognition and learning goals. Theory-centric approaches, she maintains, pursue broad disciplinary questions about the content of theories, as for instance:

- What claims is a theory or hypothesis making about natural or social worlds?
- How do these relate to claims made/supported in other theories?
- How do they relate to broader metaphysical questions?

Such questions would align with the epistemic beliefs perspective among educational psychologists advancing conceptual change theories of learning (Murphy & Alexander, 2016). On the other hand, practice-centric approaches pursue sub-disciplinary questions such as:

- What are the questions of a specific scientific sub-discipline or approach within a sub-discipline?
- What methods and strategies are employed to answer those questions?
- What do those methods and strategies produce or count as evidence?
- Are they different from the methods and strategies employed in neighboring or competing approaches?
- How is what counts as evidence brought to bear on the substantive claims being made (or “suggested”)?
- What are the standards of acceptability or acceptance employed in a given approach or subdiscipline?
- How do these practices relate to epistemological concepts like rationality, objectivity, evidence?

Longino’s (2015) perspective has salience for conceptualizing educational frameworks targeting practice-based ideas about the growth of knowledge and the nature of scientific reasoning. We think that this perspective is coherent with the AIR model (Chinn et al., 2011) discussed below. Our contemporary understanding of the NOS is that most scientific activities do not focus on testing, justification, or final theory acceptance. What dominates knowledge seeking practices in science is not, as previously believed, rooted in the context of discovery and the context of justification. The bulk of activities are attending to anomalies and refining models and mechanisms (i.e., the Practices-centric activities within sub-disciplines) that facilitate improvement and refinement of a scientific theory. The right epistemic game is the refinement of knowledge systems to enhance explanatory coherence (Duschl & Grandy, 2008; Thagard, 2007).

An adequate understanding of NOS is of course relevant, but in science education there are other dimensions related to epistemology (e.g., epistemic cognition, epistemic thinking, and epistemic practices) and different perspectives for characterizing such thinking and reasoning (e.g., personal epistemologies, productive epistemologies and practical epistemologies). We turn to a brief overview of these dimensions and perspectives.
Epistemic Cognition, Thinking and Practices

Again, in the *Handbook of Epistemic Cognition*, the editors take steps to define and refine competing perspectives among scholars. They point out that it is not clear whether contributing authors’ perspectives about phenomena are either: 1) regarding particular mental representations to be characterized as epistemic beliefs or 2) representing unique cognitive processes that activate epistemic cognition when reasoning in epistemic contexts. Sinatra (2016), in her summary chapter, suggests that a combined view is also possible, where epistemic beliefs are the content upon which epistemic cognition processes act.

Epistemic cognition refers to thinking about knowing. For Chinn, Rinehart, and Buckland (2014) and Chinn et al. (2011), the approach is grounded in both philosophy and psychology. Epistemic cognition is characterized as “a network of interrelated topics including knowledge, its sources and justification, belief, evidence, truth, understanding, explanation, and many others” (Chinn et al., 2011, p. 141). Rooted in concepts of social epistemology (Goldman, 1999), they propose the AIR model and a set of principles for epistemic cognition. The AIR model stands for Aims and values, epistemic Ideals, and Reliable epistemic processes. These principles, grounded in philosophical perspectives, claim that epistemic cognition is (a) fundamentally social; (b) situated in practices; (c) situated in problem, project, or design-based contexts; and (d) connected to ethical concerns. In the AIR model, epistemic aims are goals related to finding things out, understanding them and forming beliefs, with knowledge the most discussed epistemic aim. Ideals (standards and criteria) relate, for instance, to the specific standards people use to evaluate knowledge claims or to the criteria used to select evidence. The consistency of a belief or knowledge system may belong also to standards. Reliable processes refer to the cognitive and social processes by which knowledge and other epistemic aims are achieved. A major contribution of this research is the contributions and insights being made for the design of measures and methods to capture and analyze students’ conceptual and epistemic reasoning. Examples of the evaluation of knowledge claims reliability processes are presented in Chinn, Rinehart, and Buckland (2013).

One can ask if there is there a difference between “epistemic cognition” and “epistemic thinking.” In an effort to address the question posed by Hofer and Sinatra (2010) concerning to what degree is personal epistemology metacognitive, Barzilai and Zohar (2014, 2016) examine the relationships between both constructs, proposing to reconsider personal epistemology as metacognition. They consider the term epistemic thinking as encompassing epistemic cognition and epistemic metacognition (Barzilai & Zohar, 2016). Epistemic cognition is thinking about the epistemic characteristics of knowledge claims and their sources, as well as engaging in epistemic strategies and processes for reasoning about them. Epistemic metacognition refers to knowledge, skills and experiences regarding the nature of knowledge, and knowing strategies and processes.

The interest of Barzilai and Zohar’s (2014, 2016) frame lies in explicitly adding the metacognitive dimensions to Chinn et al.’s (2011) model. Barzilai and Zohar (2016) propose that all facets of epistemic thinking entail both domain-general and domain-specific aspects, but that different facets may have different degrees of specificity. In particular, they suggest that epistemic cognition might be more specific, and epistemic metacognition more domain-general.
In the last years there has been a shift in focus from an interest in learners’ epistemological beliefs, or personal epistemologies (Hofer & Pintrich, 1997), toward an interest in learners’ engagement in EP, sometimes termed practical epistemologies (Hammer et al., 2008; Wickman & Östman, 2002). This shift from beliefs to practices is grounded in an approach that considers science learning involving students’ development of key epistemic, cognitive and social practices (Duschl & Grandy, 2013; Jiménez-Aleixandre & Erduran, 2008; Kelly, 2008). The focus is on functional, rather than declarative, understanding of the nature of science (Allchin, 2011), on how individuals and communities generate knowledge (Chinn et al., 2011).

Kelly, McDonald, and Wickman (2012) identified three perspectives about the relationships between science learning and epistemology, each with different perspectives for research programs:

- **disciplinary** perspectives rely on philosophy of science in order to consider theory change or conceptual change in science learning;
- **personal** perspectives concern the ways students’ personal epistemologies influence learning; and
- **social practices** view considers ways by which disciplinary practices—as, for instance, engaging in special discourse—are enacted in learning contexts.

Jimenez-Aleixandre and Duschl (2015) find value in thinking about a progression in science education approaches to epistemology: from personal epistemologies through productive epistemologies to practical epistemologies. Jimenez-Aleixandre and Duschl (2015) characterize the three epistemologies as:

- **Personal epistemologies**: focus on students’ views about the nature of science (NOS), on consensus about what would represent a sophisticated view about it (Hofer & Pintrich, 1997).
- **Productive epistemologies**: focus on students’ views and resources, assessed with criteria different from the consensus view.
- **Practical epistemologies**: focus on students’ enactment of disciplinary practices in learning contexts.

Wickman and Östman (2002) and Wickman (2004) coined the term *practical epistemologies* to reference students’ epistemologies as used in specific practices. Practical epistemologies are viewed as actions, rather than as beliefs, wherein students’ and teachers’ actions are situated in an activity (Wickman, 2004). Östman and Wickman (2014) refer to their approach as practical epistemological analysis (PEA), pointing out that practical epistemologies concern a view of learning as the transformation of observable habits in action.

The implication of focusing on epistemic practices and epistemic cognition resides in the ways that evidence, measurement, models and use of tools and data texts constitute the language and practices of science. The language of science includes mathematical, stochastic, representational and epistemological elements, as well as domain-specific descriptors and forms of evidence. The challenge for science education researchers and practitioners, as well as researchers designing and developing performance assessments
that guide and inform learning, is one of understanding how to mediate, progress and coordinate language and knowledge acquisition in these various and typically domain-specific epistemic and social practices.

Design of Learning Environments: Practices, Reasoning, and Discourse

The emergent tradition for the teaching and learning of science is to frame learning in contexts that merge content knowledge with skills, practices, and processes. The naturalistic turn in philosophy of science, with its focus on activities and practices that are cognitive, epistemic and social, has implications for science learning and the framing of research on science learning and reasoning. 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 (Hapgood, Magnusson & Palincsar, 2004; Ford, 2005; Metz, 1995; NRC, 2007; Slavin, Lake, Hanley, & Thurston, 2014; Trygstad, Smith, Banilower, & Nelson, 2013). 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 and making American curricula “a mile wide and an inch deep” (Nowicki, Sullivan-Watts, Shim, Young, & Pockalny, 2013; Schmidt, McKnight, & Raizen, 1997); (b) in the case of middle school textbooks, tend to present science topics as unrelated items with little or no regard to relations among them (Keisdou & Roseman, 2002); and (c) do not adequately prepare elementary science teachers (McConnell, Parker, & Eberhardt, 2013; Nowicki et al., 2013; Rice & Kaya, 2012).

Metz (2008) also finds that “science curricula have frequently been critiqued as reflecting an impoverished model of the practices of scientific knowledge construction” (p. 139). First, there is her critique that the reasoning capacities of children have been underestimated because when they are tested and found to be weak, this can be due to weak domain knowledge. Brown (1990) found differences in knowledge as the basis for apparent superiority in the reasoning of preschoolers. A second reason given for underestimating children’s capabilities is that cognitive development research has not paid attention to the important role of instruction (Metz, 2008).

Ohlosson (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 third-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 Ford laments 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), Smith (2007), among others, to investigate ways to design classroom learning environments that promote students’ theory and model building reasoning.

Lehrer and Schauble (2006b) 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; (1) finding ways to help students understand and appropriate the process of scientific inquiry, (2) emphasizing the development and use of varying forms of representations and inscriptions, and, (3) capitalizing on the cyclical nature of modeling.

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 the purposes of experimentation made a difference. Other reports of research that have found positive learning effects of 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), Toth, Suthers, and Lesgold (2002) and Songer and Linn (1991).

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, Warren, and Conant’s study spanned an entire school year while that of Smith, Maclin, Houghton, and Hennessey followed a cohort of students for several years with the same teacher. Both studies used classroom practices that place a heavy
emphasized on (1) requiring evidence for claims, (2) evaluating the fit of new ideas to data, (3) justifications for specific claims and (4) 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 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 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 & Inagaki (1991), Herrenkohl and Guerra used the audience role procedures to engage students in (1) asking clarification questions; (2) challenging others’ claims; and, (3) coordinating bits of knowledge. The focus on listening skills and audience roles helps to foster productive community discourse around students thinking in science.

**SUMMARY**

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. 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, learners develop images of systems thinking, of the nature of science, and of scientific inquiry as an enterprise that is fundamentally a model-based reasoning and refining process. Viewing formal and informal learning environments as a scientific community where learners participate in science practices and discourse processes akin to professional communities is under-studied and more research is needed.

Research on developmental trajectories/progressions that examine learning and reasoning is important and, while it is informed by lab studies and cross-age interview data, it 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 undergraduate STEM environments.
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 recent NRC 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* emphasize 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.

Another aspect of going further is to study how teachers are engaging in such new pathway sequences of instructional units. That is, how do teachers 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 and assessments 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 agendas 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. The rewards will be many as we develop richer understandings about the cultivation and motivation of PreK–16 STEM learning and teaching.

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