Chapter 8

Science Education in Three-Part Harmony: Balancing Conceptual, Epistemic, and Social Learning Goals

RICHARD DUSCHL
Rutgers, the State University of New Jersey, New Brunswick

Two major reform efforts in K–12 science education have taken place during the past 50 years. The first was the 1950–1970 curriculum reform efforts motivated by the launching of Sputnik and sponsored by the newly formed National Science Foundation (NSF) in the United States and by the Nuffield Foundation in the United Kingdom. The signature goal for these reformed programs was to produce courses of study that would get students to "think like scientists," thus placing them in a "pipeline" for science careers (Rudolph, 2002).

The second U.S. and U.K. reform effort in science education began in the 1980s and continues to this day as part of the national standards movement. Referred to as the "Science for All" movement in the United States and the "Public Understanding of Science" in the United Kingdom, here the education goal was and is to develop a scientifically literate populace that can participate in both the economic and democratic agendas of our increasingly global market–focused science, technology, engineering, and mathematics (STEM) societies. In addition to the economic and democratic imperatives as a purpose for science education, more recent voices of science education reform (Driver, Leach, Millar, & Scott, 1996; Millar, 1996; Millar & Hunt, 2002; Osborne, Duschl, & Fairbrother, 2002) have advocated that the proper perspective for science education in schools ought to be the cultural imperative. The cultural imperative perspective sees STEM disciplines, knowledge, and practices as woven into the very fabric of our nations and societies. What the cultural imperative provides that the democratic and economic imperatives do not is recognition of important social and epistemic dimensions that are embedded in the growth, evaluation, representation, and communication of STEM knowledge and practices. New perspectives and understandings in the learning sciences about learning and learning environments, and in science studies about knowing and inquiring, highlight the importance of science

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education teaching and learning harmonizing conceptual, epistemological, and social learning goals.

Traditionally, science curriculum has focused on what one needs *to know* to do science. Schwab (1962) called this the "rhetoric of conclusions" approach to science education, and he advocated that science education be an "enquiry into enquiry." Thirty years later, Duschl (1990) commented on the problem of "final form science" instruction, a signal that little progress had been made toward shifting the focus of science education from what we know to how we know and why we believe. The new perspective of science education focuses on what students need *to do* to learn science. The notion of *to do* in science education has traditionally been associated with the manipulation of objects and materials to engage learners with phenomena to teach what we know. This is embodied in disconnected, modularized, hands-on and textbook approaches that have been a hallmark of elementary and secondary science curricula since the 1960s reform efforts. The dominant format in curriculum materials and pedagogical practices is to reveal, demonstrate, and reinforce via typically short investigations and lessons either (a) "what we know" as identified in textbooks or by the authority of the teacher or (b) the general processes of science without any meaningful connections to relevant contexts or the development of conceptual knowledge. What has been missing is a sense of *to do* that embodies the dialogic knowledge-building processes that are at the core of science, namely, obtaining and using principles and evidence to develop explanations and predictions that represent our best-reasoned beliefs about the natural world. In other words, missing from the pedagogical conversation is how we know what we know and why we believe it.

Two recent National Research Council (NRC) reports—*Rising Above the Gathering Storm* (*RAGS*; NRC, 2007a) and *Taking Science to School: Learning and Teaching Science in grades K–8.* (*TSTS*; NRC, 2007b)—serve as evidence, though, that competing perspectives and agendas in science education persist. The *RAGS* report is a response to STEM workforce issues, for example, shortages in attracting and retaining students and teachers in science programs and careers. The *TSTS* report reflects new research understandings about how children learn science and how to design and implement effective science learning environments. The *RAGS* report emphasizes the economic imperative of keeping the United States competitive in STEM global markets. The *RAGS* focus is on the "pipeline," the emergence of new interdisciplinary sciences, the integration of sciences and technologies, and the need for more Advanced Placement courses at the high school level.

The *TSTS* report puts emphasis on the cultural imperative and harmonizing learning goals by advocating the development of four strands of scientific proficiency for all students. Students who understand science

1. know, use, and interpret scientific explanations of the natural world;
2. generate and evaluate scientific evidence and explanations;
3. understand the nature and development of scientific knowledge; and
4. participate productively in scientific practices and discourse.

The four strands of scientific proficiency reflect an important change in focus for science education, one that embraces a shift from teaching about *what* to teaching about *how* and *why*. But as one of the *TSTS* research recommendations indicates, more research knowledge exists for how children perform in Strands 1 and 2 than exists for children's performance in Strands 3 and 4.

The focus of this chapter is to examine research and development efforts on the critical role epistemic understanding and scientific reasoning play in the development of understanding science. The first section of the chapter presents an overview of salient developments in two new scholarly domains—learning sciences and science studies—that inform the framing of research on epistemic reasoning and learning goals in science education. The second section examines specific programs of research that seek to develop classrooms as epistemic communities. The third and final section moves to a discussion of the design of science curriculum, instruction, and assessment models. Issues are raised about what constitutes the appropriate "grain size" of ideas, evidence, information, and explanations for K–12 science education that seeks to harmonize across conceptual, epistemic, and social learning goals.

SHIFTING THE AGENDA IN SCIENCE EDUCATION

The agenda for science education has broadened in ways that demand a rethinking of approaches to curriculum, instruction, and assessment. We live in a time when there is rapid growth of scientific knowledge, scientific tools and technologies, and scientific theories. Like the first science education reformers in the 1950s and 1960s, we are today faced with the challenge of making important decisions about what and how to teach. But unlike the 1960s reform effort, we now have a deeper understanding of how and under what conditions learning occurs. We also have a richer understanding of the dynamics occurring in the growth of or advancements in scientific knowledge. Essentially, we have learned about learning through advancements in two scholarly domains that can help us in our thinking about how to reform K–12 science education:

1. Learning sciences: A group of disciplines focusing on learning and the design of learning environments that draw from cognitive, developmental, and social psychology; anthropology; linguistics; philosophy of mind; artificial intelligence; and educational research.
2. Science studies: A group of disciplines focusing on knowing and inquiring that draw from history, philosophy, anthropology, and sociology of science as well as cognitive psychology, computer science, science education, and artificial intelligence.

It is well beyond the scope of this chapter to provide a thorough review of developments in these two domains. An overview follows below. For comprehensive reviews of developments in the learning sciences, interested readers are directed to recent NRC (1999, 2001, 2007b) reports and to *The Cambridge Handbook of the Learning Sciences* (Sawyer, 2006). For overviews and commentary on the emergence of science studies, refer to Godfrey-Smith (2003), Longino (2002), Kitcher (1993, 1998), Koertge (1998), and Zammito (2004).

Learning Sciences

What the learning sciences literature tells us is that the structure of knowledge and the processes of knowing and learning are much more nuanced than initially described by associative and behavioral learning theories. That is, context and content matter. Thus, there is a general move away from an emphasis on domain-general reasoning and skill development to domain-specific reasoning and practices development. The richer understanding of learning and reasoning domain-specific contexts provide has significant implications for the design of pedagogical models and learning environments.

In a review article titled "The Psychology of Learning: A Short History," Bruner (2004) concludes, "It was the cognitive revolution that brought down [associative and behavioral] learning theory" and "it was the study of language and particularly of language acquisition that precipitated learning theory's decline" (p. 19). The cognitive, social, and cultural dynamics of learning are mutually supportive of one another and intertwined such that "you cannot strip learning of its content, nor study it in a 'neutral' context. It is always situated, always related to some ongoing enterprise" (Bruner, 2004, p. 20). In this sense, psychologists claim that learning has a historical dynamic because learning is shaped by experiences, by the sequencing of those experiences, and by the guiding hand of thoughtful mediation directed toward learning goals (Lehrer & Schauble, 2006b; Rogoff, 1990).

One domain in particular from the learning sciences has helped us understand cognitive development; it is research on infants' and children's learning (NRC, 2007b). This new field of scholarly work reveals how infants and young children are capable of abstract reasoning in core knowledge domains of science and mathematics (e.g., change, form, and function; physical attributes and properties of objects; systems and interactions; number sense; causal inference; distinguishing animate from inanimate). Researchers are learning that young children are capable of complex reasoning, for example, theory building. These and other forms of scientific reasoning are possible when children are provided with multiple opportunities that sustain their engagement with select scientific practices over time such as predicting, observing, testing, measuring, counting, recording, collaborating, and communicating (Carey, 2004; Gelman & Brenneman, 2004; Gopnik et al., 2004; Hapgood, Magnusson, & Palincsar, 2004; Metz, 2004; Spelke, 2000).

Schauble (2007) reminds us, though, that although 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)

The study of infants and child development is but one important element of the learning sciences. Sawyer (2006), in the preface of *The Cambridge Handbook of the Learning Sciences*, states that the "goal of the learning sciences is to better understand the cognitive and social processes that result in the most effective learning" (p. xi). The emergence of the learning sciences community in the past three decades has shifted the educational and developmental research agenda to the redesign of classrooms and other out-of-school learning environments. The stakeholders in the design of classrooms and learning environments are teachers, parents, administrators, policymakers, and professionals. The learning science constructs for such redesign include (a) transition from novice to expert performance, (b) using prior knowledge, (c) scaffolding, (d) externalization and articulation, (e) reflection, and (f) building from concrete to abstract knowledge.

The learning sciences emerged from the earlier constructivist theories of learning and from the pioneering research in the cognitive sciences. Our deeper understanding of how children's thinking is fundamentally different from that of adults, coupled with richer understandings of expertise, representation, reflection, problem solving, and thinking, provided a foundation for a major tenet of the learning sciences: "Students learn deeper knowledge when they engage in activities that are similar to the everyday activities of professionals who work in a discipline" (Sawyer, 2006, p. 4). Subsequent research on informal learning reveals the importance of participation structures and the development of practices in culturally valued activities (Cole, 1996). Focusing on scaffolding, apprenticeship, legitimate peripheral participation, and guided participation, informal learning researchers provided "broader units of analysis . . . : these views move beyond the study of individuals alone to consider how learning occurs within enduring social groups such as families and communities" (Bransford et al., 2006, p. 24).

One element of the learning sciences and an important dynamic of relevance here is the development of expertise within and among knowledge workers, for example, scientists, engineers, mathematicians, medical doctors, and so on. Cognitive, historical, sociological, and anthropological studies of knowledge workers revealed the importance of practices that are central to the professional activities in these knowledge growth communities. With respect to the scientific disciplines and, in particular, the study of epistemic cultures, cognitive models of science (cf. Giere, 1988; Goldman, 1986; Kitcher, 1993; Thagard, 1992) coupled with sociocultural models of science (cf. Knorr-Cetina, 1999; T. Kuhn, 1962/1996; Longino, 1990, 2002) have established the important role that models, mechanisms, and peers have in the advancement and refinement of scientific knowledge and the methods regarding the growth of scientific knowledge. Science takes place in complex settings of cognitive, epistemic, and social practices.

The implication for science learning is that more and more contemporary science is being done at the boundaries of disciplines. Thus, there is a connectedness in the practices of science that are not typically found in school classroom environments. An examination of school curriculum, for example, reveals disconnected and isolated units of instruction the norm in K–8 science education (NRC, 2007b). An examination of the growth of scientific knowledge as provided by science studies scholars can provide some helpful insights on how to proceed with the redesign agenda.

Science Studies

In very broad brushstrokes, 20th-century developments in science studies can be divided into three periods. In the first, logical positivism, with its emphasis on mathematical logic and the hypothetico-deductive method, was dominant. Some of the major figures in the movement were Rudolf Carnap, Carl G. Hempel, Ernest Nagel, and Hans Reichenbach. Logical positivism views of science held to several assumptions:

1. There is an epistemologically significant distinction between observation language and theoretical language, and this distinction can be made in terms of syntax or grammar.
2. Some form of inductive logic would be found that will provide a formal criterion for theory evaluation.
3. There is an important dichotomy between contexts of discovery and contexts of justification.

In the 1950s and '60s, various writers questioned these and other fundamental assumptions of logical positivism and argued for the relevance of historical and psychological factors in understanding science. Thomas S. Kuhn is the best known of the figures in this movement, but there were numerous others, including Paul Feyerabend, Norwood Russell Hanson, Mary Hesse, and Stephen Toulmin.

T. Kuhn (1962/1996) introduced the conception of paradigm shifts in the original version of *The Structure of Scientific Revolutions* and then revised it in the postscript to the 1970 second edition, introducing the concept of a disciplinary matrix. One important aspect of Kuhn's work was the distinction between revolutionary and normal science. Revolutionary science involves significant conceptual changes, whereas normal science consists of "puzzle solving," of making nature fit into the boxes specified by the disciplinary matrix.

In this view of science, theories still played a central role, but they shared the stage with other elements of science, including a social dimension. Although Kuhn saw the scientific communities as essential elements in the cognitive functioning of science, his early work did not present a detailed analysis. The most recent movements in philosophy of science can be seen as filling in some of the gaps left by Kuhn's demolition of the basic tenets of logical positivism. This movement

1. emphasizes the role of models and data construction in the scientific practices of theory development,
2. sees the scientific community as an essential part of the scientific process, and
3. sees the cognitive scientific processes as a distributed system that includes instruments, forms of representation, and agreed upon systems for communication and argument.

Science is seen as having important social phenomena with unique norms for participation in a community of peers. Perhaps the most important element Kuhn and others added to our understanding of the nature of science is the recognition that most of the theory change that occurs in science is not final theory acceptance but improvement and refinement of a theory. Ninety-nine percent of what occurs in science is neither the context of discovery nor the context of justification, as the logical positivists proposed, but the context of theory development, of conceptual modification. The dialogical processes of theory development and of dealing with anomalous data occupy a great deal of scientists' time and energy. The logical positivist's context of justification is a formal final point—the end of a journey; moreover, it is a destination few theories ever achieve, and so overemphasis on it entirely misses the importance of the journey. Importantly, the journey involved in the growth of scientific knowledge reveals the ways in which scientists respond to new data, to new theories that interpret data, or to both. Some people describe this feature of the scientific process by saying that scientific claims are tentative; I prefer to say that science and scientists are responsive, thus avoiding the connotation that tentative claims are unsupported by evidence or scientific reasoning.

One of the important findings from the science studies literature is that not only does scientific knowledge change with time, but so, too, do the methods of inquiry and the criteria for the evaluation of knowledge change. The accretion growth model of scientific knowledge is no longer tenable. Nor is a model of the growth of knowledge that appeals to changes in theory commitments alone, for example, a conceptual change model. Changes in research programs that drive the growth of scientific knowledge also can be because of changes in methodological commitments or goal commitments (Duschl, 1990). Science studies examining contemporary science practices recognize that both the conceptual frameworks and the methodological practices of science have changed with time. Changes in methodology are a consequence of new tools, new technologies, and new explanatory models and theories that, in turn, have shaped and will continue to shape scientific knowledge and scientific practices.

As science has progressed as a way of knowing, yet another dichotomy has emerged, and it is one that is critically important for a contemporary consideration of the design of K–12 curriculum, instruction, and assessment. That dichotomy is the blurring of boundaries between science and technology and between different branches of the sciences themselves, yet another outcome of learning how to learn that challenges our beliefs about what counts as data, evidence, and explanations. Ackerman (1985) refers to such developments as the shifts in the "data texts" of science and warns that the conversations among contemporary scientists about measurement, observations, data, evidence, models, and explanations is of a kind that is quite foreign from the conversations found in the general population. Consequently, understanding discipline-based epistemic frameworks, as opposed to or in addition to learning-based epistemic frameworks, is critically important for situating school science learning, knowing, and inquiry (Hammer & Elby, 2003; Kelly & Duschl, 2002).

Pickering (1995) referred to this conflation when describing experiments in high-energy physics as the "mangle of practice." Zammito (2004) writes,

> Pickering's (1990) "practical realism" or interpretation of "science as practice" offers a robust appreciation for the *complexity* of science, its "rich plurality of elements of knowledge and practice," which he has come to call the "the mangle of practice." Indeed, as Ian Hacking (1988) has noted, it is the "richness, complexity and variety of scientific life" which has occasioned the widespread new emphasis on science as practice. As against the "statics of knowledge," the frame of existing theoretical ideas, Pickering (1990) situates the essence of scientific life in the "dynamics of practice," that is, "a complex process of reciprocal and interdependent tunings and refigurings of material procedures, interpretations and theories." (pp. 225–226)

For Pickering, scientific inquiry during its planning and implementation stages is a patchy and fragmented set of processes mobilized around resources. Planning is the contingent and creative designation of goals. Implementation for Pickering (1989) has

> three elements: a "material procedure" which involves setting up, running and monitoring an apparatus; an "instrumental model," which conceives how the apparatus should function; and a "phenomenal model," which "endows experimental findings within meaning and significance . . . a conceptual understanding of whatever aspect of the phenomenal world is under investigation. The "hard work" of science comes in trying to make all these work together. (Zammito, 2004, pp. 226–227)

The role of modeling practices in science and of model-based reasoning has led Lehrer and Schauble (2006a), among others, to investigate ways to design classroom learning environments that promote students' modeling and model-based reasoning. This research focus has, in turn, contributed to new views about the image of science we present to students in school science. The *TSTS* report (NRC, 2007b) interprets these science studies perspectives by stating that science involves the following important epistemic and social practices:

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

Science Education

The "pipeline" curriculum agenda is a pushdown curriculum driven by scientists' perspectives of what one needs to know to do science. This orientation was criticized right from the inception of early NSF curricula (Duschl, 1990; Easley, 1959; Rudolph, 2005). The science-for-scientists approach initially ignored research on teaching and learning in the conceptualization and design of science curricula. What ensued, then, was a content–process (CP) curriculum orientation in school science that typically separated one, content learning, from the other, process learning. A competing curriculum orientation is the discovery–inquiry (DI) approach to teaching science introduced during the NSF curriculum reform movement of the 1950s and 1960s, characterized by Rudolph (2002) as the scientist-in-the-classroom period of U.S. science education.

Although the many initial ideas of Schwab (1958, 1962) to orient science learning to an "enquiry of enquiry" and thereby avoid the "rhetoric of conclusions" conditions found in classrooms still have cachet today, something got lost in the translation to curriculum materials. What got lost in the design of inquiry curriculum materials was the focus on the important roles that guiding conceptions, evidence, and explanations have in framing the syntactic, semantic, and pragmatic structures of scientific inquiry, namely, the epistemic criteria, the conceptual clusters, and the experimental and knowledge-building practices used when doing science (Duschl & Grandy, 2007).

Since the first NSF-funded era of science education reform in the 1960s and 1970s, we see a shift in views about the nature of science from science as experimentation to science as explanation and model building, from science inquiry as an individualistic process to scientific inquiry as an individual and social process, and from science teaching focusing on the management of learners' behaviors and hands-on materials to science teaching focusing on the management of learners' ideas, access to information, and interactions between learners. Some of the shifts have been motivated by new technological development, but new theories about learning, as mentioned above, have contributed, too.

One important change that has significant implications for school science concerns the realm of scientific observations and representations. In the past 100 years, new technologies and new scientific theories have modified the nature of scientific observation from an enterprise dominated by sense perception, aided or unaided, to a theory-driven enterprise (Duschl, Deak, Ellenbogen, & Holton, 1999). We now know that what we see is influenced by what we know and by how we "look." In this sense, scientific theories are inextricably involved in the design and interpretation of experimental methods and scientific instrumentation. The implication is that there are additional important details for the development of learners' scientific literacy, reasoning, and images about the nature of science.

Consider that the developments in scientific theory coupled with concomitant advances in material sciences, engineering, and technologies have given rise to radically new ways of observing nature and engaging with phenomenon. At the beginning of the 20th century, scientists were debating the existence of atoms and genes; by the end of the century, they were manipulating individual atoms and engaging in genetic engineering. These developments are representative of the disciplinary details (conceptual, epistemic, and social) that are altering the nature of scientific inquiry and have greatly complicated our images of what it means to engage in scientific inquiry. Whereas once scientific inquiry was principally the domain of unaided sense perception, today scientific inquiry is guided by highly theoretical beliefs that determine the very existence of observational events (e.g., neutrino capture experiments in the ice fields of Antarctica). Whereas once scientific inquiry was practiced by individuals or small groups with established patrons, today scientific inquiry involves large international communities of university and industrial scientists guided by complimentary or competing beliefs and goals, often fighting for limited governmental grants to enable the research.

Scientific databases such as Geographical Information Systems make it possible to engage in rich scientific inquiry without engaging in hands-on science involving the collection of data. Instead, the data are provided and the inquiry begins with the selection of information for analysis. This is one example of how science education has shifted from management of materials for collecting data to management of information for scrutinizing databases. Such a shift has implications regarding the manner in which interactions with phenomena are designed and included in science lessons for all grade levels and the level of details we elect to include pursue. Information in the guise of data, evidence, models, and explanations represents, in an important sense, the new materials for school classrooms and laboratories.

Historically, scientific inquiry has often been motivated by practical concerns; for example, improvements in astronomy were largely driven and financed by the quest for a better calendar, and thermodynamics was primarily motivated by the desire for more efficient steam engines. But today, scientific inquiry underpins the development of vastly more powerful new technologies and addresses more pressing social problems, for example, finding clean renewable energy sources, feeding an exploding world population through genetically modified food technologies, and stem cell research. In such pragmatic problem-based contexts, new scientific knowledge is as much a consequence of inquiry as the goal of inquiry. New tools, new theories, and new technologies have contributed to advances in science such that the very foundational acts of science, such as observation and measurement, have evolved to the point that direct human interactions are no longer required. As mentioned above, entities such as genes and atoms whose existence and precise nature were debated a mere two generations ago are now being manipulated.

The findings from science studies and from the learning sciences suggest new conceptions for school science and new designs for learning environments in terms of models of curriculum, instruction, and assessment. A new generation of educational researchers is turning attention to design research with a shared goal of sorting out the proper trajectories, developmental pathways, or learning progressions that support the growth of knowledge and the development of reasoning. Within this domain of research, epistemic practices are among the salient topics of inquiry. Thus, there is attention to the design of learning environments as epistemic communities of practice.

EPISTEMIC COMMUNITIES OF PRACTICE

When we synthesize the learning sciences research (NRC, 1999, 2001; Sawyer, 2006), the science studies research (cf. Giere, 1988, 1999; Longino, 2002; Nersessian, 1992), and science education research (cf. Millar, Leach, & Osborne, 2000; Minstrell & van Zee, 2000; NRC, 2007b) we learn the following:

1. The incorporation and assessment of science learning in educational contexts should focus on three integrated domains:
    - the *conceptual* structures and *cognitive* processes used when reasoning scientifically,
    - the *epistemic* frameworks used when developing and evaluating scientific knowledge, and
    - the *social* processes and contexts that shape how knowledge is communicated, represented, argued, and debated.

2. The conditions for science learning and assessment improve through the establishment of
    - learning environments that promote *active productive student learning*,
    - instructional sequences that promote *integrating science learning* across each of the three domains listed above in paragraph 1,
    - activities and tasks that *make students' thinking visible* in each of the three domains, and
    - teacher-designed assessment practices that *monitor learning and provide feedback* on thinking and learning in each of the three domains.

Taken together, the recent developments in the learning sciences and science studies have implications for how we conceptualize the design and delivery of science curriculum materials for purposes of supporting students' learning as well as teachers' assessments for promoting learning. However, existing curricula rarely provide these kinds of experiences and learning opportunities (Duschl & Grandy, 2007; Ford, 2005; Hapgood et al., 2004; NRC, 2007b).

Why is this the case? Well, one partial answer, the psychological component, is because of a lack of research on how children learn and develop scientific knowledge and inquiry practices over time when guided with competent instruction, Schauble's (2007) second and third questions above. A second partial answer, the philosophical component, is the image of science that prevails in science education. What does it mean to be doing science? Is it fundamentally about conducting experiments and testing hypotheses? Is it fundamentally about building theories? Or is it fundamentally about participating in a community of practice that uses and tests models that explain the results of experiments and that inform the structure of theories? A third partial answer, the pedagogical component, concerns the teaching and communication of science. What is most worth knowing? Is it what we know? Or is it how we know and why we believe it even in the face of plausible competing alternatives?

The focus and goals of precollege science education have shifted. In brief, the almost exclusive emphases on conceptual goals of science learning are making room for epistemic and social learning goals. In the rapidly changing world of STEM activities, an understanding of criteria for evaluating knowledge claims, that is, deciding what counts, is as important as an understanding of conceptual frameworks for developing knowledge claims. The relation needs to be a symbiotic one; this is not an either–or situation. Conceptual and epistemic learning should be concurrent in science classrooms, situated within curriculum, instruction, and assessment models that promote the development of each. Moreover, they should reinforce each other, even mutually establish each other. To accomplish a redesign of science learning environments, new perspectives regarding the role of CP and DI approaches to science education are needed.

The history of science education since World War II shows numerous attempts to move instruction away from textbooks and lectures to investigations and experiments (Rudolph, 2002, 2005). Curriculum materials were developed to prepare the next generation of scientists, and lessons were written to help students think like scientists. The CP continuum is the dominant paradigm of science education: "Here is what we know and this is how we go about getting the knowledge," where getting the knowledge is following the testing hypothesis scientific method. The persistence of the CP continuum today seems to have more to do with the adherence to the old view of scientific methods and to the way schools are run and organized and less to do with what we understand about effective learning environments and children's learning (NRC, 2007b).

The rival DI continuum was introduced during the time of the 1950s-to-1960s curriculum and teacher-development interventions. The recent focus on science as inquiry in the United States suggests that the DI approach has not made inroads on the CP science education practices. The NRC's (1996) *National Science Education Standards* and *Inquiry and the National Science Education Standards* (NRC, 2000), along with the edited book *Inquiring Into Inquiry Learning and Teaching in Science* (Minstrell & van Zee, 2000), clearly signal dissatisfaction with school science programs that continue to promote CP orientations.

Many of the extant K–8 science curriculum programs have been found wanting in terms of the lean reasoning demands required of students (cf. Ford, 2005; Hapgood et al., 2004; Metz, 1995; NRC, 2007b). 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 is partially because of a lack of consensus about what is most worth learning, for example, the "big ideas" or core knowledge of early science learning, and because of K–8 teachers' 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, thus making American curricula "a mile wide and an inch deep" (Schmidt, McNight, & Raizen, 1997); and (b) in the case of middle school textbooks, tend to present science topics as unrelated items with little or no regard to relations between them (Kesidou & Roseman, 2002).

An alternative to the CP and DI approaches is to consider dialectical discourse frameworks based on an evidence–explanation (E-E) continuum that engage learners in conversations of inquiry. Driven by a consideration of the growth of scientific knowledge and coupled with analyses of the cognitive and social practices of scientists, the E-E focus is on engaging learners in conversations examining "science-in-the-making" practices (Kelly, Chen, & Crawford, 1998). During science-in-the-making episodes, the detailed dialectical exchanges between observations and theory and the accompanying data texts play out. The scientific knowledge we hold is put into practice and tested. Importantly, here is how and when the important dialectical discourses about data representations, data and conceptual models, evidence, explanatory theories, and methods are incorporated into science learning environments. An important issue for school science is deciding at what level of detail and in what sequence.

The E-E continuum (Duschl, 2003) has its roots in perspectives from science studies and connects to cognitive and psychological views of learning. The call for conversations is recognition of the value and importance that representation, communication, and evaluation play in science learning. I use *conversation* in a very broad sense to include, among others ideas, argumentation, debate, modeling, drawing, writing, and other genres of language. Such an expanded repertoire helps us to consider an important domain of research in both formal and informal science learning settings, namely, how to mediate the learning experiences.

The position advanced by Schauble, Leinhardt, and Martin (1997) and Pea (1993), and adopted here, is that such learning mediations should focus on promoting talk, activity structures, signs and symbol systems, or collectively what I will call *conversations*. For science learning, the conversations should mediate the transitions from evidence to explanations, or vice versa, and thereby unfold discovery and inquiry. Adopting an image of science education that is guided by the development, evaluation, and deployment of data texts is grounded in the idea that scientific inquiry and scientific reasoning are both fundamentally decision-making activities mediated by epistemological, cultural, and technological factors. The appeal to adopting the E-E continuum as a framework for designing science education curriculum, instruction, and assessment models is that it helps work out the details of the epistemic discourse processes. The E-E continuum recognizes, whereas the CP and DI approaches do not, how cognitive structures and social practices guide judgments about scientific data texts. It does so by formatting into the instructional sequence select junctures of reasoning, for example, *data texts transformations*. At each of these junctures or transformations, instruction pauses to allow students to make and report judgments. Then students are encouraged to engage in rhetoric–argument, representation–communication and modeling–theorizing practices. The critical transformations or judgments in the E-E continuum include

1. selecting or generating data to become evidence,
2. using evidence to ascertain patterns of evidence and models, and
3. employing the models and patterns to propose explanations.

Another important judgment is, of course, deciding what data to obtain and what observations or measurements are needed (Lehrer & Schauble, 2006a, 2006b; Petrosino, Lehrer, & Schauble, 2003). The development of measurement to launch the E-E continuum is critically important. Such decisions and judgments are critical entities for explicitly teaching students about the nature of science (Duschl, 2000; Kenyon and Reiser, 2004; L. Kuhn & Reiser, 2004). How raw data are selected and analyzed to be evidence, how evidence is selected and analyzed to generate patterns and models, and how the patterns and models are used for scientific explanations are important "transitional" practices in doing science. Each transition involves data texts and making epistemic judgments about "what counts." The complex relationship between evidence and explanation in science warrants an examination of the tools we teach children to use (e.g., Tinkerplots) and of changes or boundary adjustments in three kinds of criteria children employ to relate evidence to explanation: (a) criteria for assigning data to one of four categories: fact, artifact, irrelevant, or anomalous; (b) criteria for identifying patterns or models in selected data; and (c) criteria for theories or explanations created to account for the patterns or models (Duschl, 2000). The preceding discussion sets out some of the challenges and attending scientific inquiry details that face recommendations to redesign science learning environments.

Designing Epistemic Learning Environments

Recall from the introduction of the chapter that there is a need for more research on the third and fourth strands of scientific proficiency, "Understand the nature and development of scientific knowledge" and "Participate productively in scientific practices and discourse." There is, however, some good recent research contributing to our understandings of learning environments that advance in tandem (e.g., harmonize) epistemic, social, and conceptual learning.

Lehrer and Schauble (2006a) report on a 10-year program of research that examines model-based reasoning and instruction in science and mathematics. Critical to the design of these learning environments is engagement in analogical mapping of students' representational systems and emergent models to the natural world. Important instructional supports are coordinated around three forms of collective activity: (a) finding ways to help students understand and appropriate the process of scientific inquiry, (b) emphasizing the development and use of varying forms of representations and inscriptions, and (c) capitalizing on the cyclical nature of modeling (p. 381).

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 that 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 although students have productive epistemic resources to bring to inquiry, there is a need to deepen the epistemic discourse on 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" (Sandoval, 2003, 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 (e.g., the E-E continuum transformations described above) and that examine how what comes to count as evidence depends on careful observations and building of 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 compared to students who simply enacted the investigations. 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 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, whereas 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 emphasis on (a) requiring evidence for claims, (b) evaluating the fit of new ideas to data, (c) justifications for specific claims, and (d) examining methods for generating data. Engle and Conant (2002) refer to such classroom discourse as "productive disciplinary engagement" when it is grounded in the disciplinary norms for both social and cognitive activity.

The research by van Zee and Minstrell (1997) shows the positive gains in learning that come about when the authority for classroom conversation shifts from the teacher to the students. Employing a technique they call the "reflective toss," van Zee and Minstrell found that students become more active in the classroom discourse, with the positive consequence of making student thinking more visible to both the teacher and the students themselves. Herrenkohl and Guerra (1998) examined the effect on student engagement of guidelines for students who constituted the audience; that is, the scaffolding was on listening to others. The intellectual goals for students were predicting and theorizing, summarizing results, and relating predictions, theories, and results. The audience role assignments were designed to correspond with the intellectual roles and required students to check and critique classmates' work. Students were directed to develop a "question chart" that would support them in their intellectual roles, that is, what questions they could ask when it was their 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? and Did you like what happened? Following the framework developed by Hatano and Inagaki (1991), Herrenhkohl and Guerra used the audience-role procedures to engage students in (a) asking clarification questions, (b) challenging others' claims, and (c) coordinating bits of knowledge. The focus on listening skills and audience roles helps to foster productive community discourse on students' "thinking in science."

LEARNING PROGRESSIONS: WHAT GRAIN SIZE KNOWLEDGE CLAIMS?

A critical aspect to the development of domain knowledge and reasoning is the appropriation of language in that domain (Gee, 1996; Lemke, 1990). The implication of focusing on evidence, measurement, models, and other data texts (Ackerman, 1985) is that the language of science is different from normal conventions or conceptions of language. The language of science includes mathematical, stochastic, representational, and epistemological elements as well as domain-specific descriptors and forms of evidence. The challenge for learning sciences research that seeks to understand and promote dialogic processes is one of understanding how to mediate and coordinate language acquisition in these various forms of communicating and representing scientific claims. A tension in science education has been deciding the right balance between domain-general learning goals (e.g., control of variables reasoning) and domain-specific learning goals (e.g., building and revising explanatory models). Another tension is deciding the balance between generalized investigative process skills and situated scientific practices.

The thesis being developed in this chapter is to move science education away from a dominant focus on conceptual learning toward a more balanced focus among things conceptual, epistemic, and social. Such a shift has significant implications for the design of curriculum, instruction, and assessment frameworks. For example, one emerging issue in science education, posed as a recommendation from *TSTS* (NRC, 2007b), is to develop learning progressions that function across grade bands, for example, 2 to 5 or 4 to 8. To address the fragmented curriculum problem, one recommendation from the NRC report is to adopt curriculum sequences that facilitate student learning; one of the *TSTS* report conclusions is to begin researching the design of learning progressions. The conclusion states,

> Sustained exploration of a focused set of core ideas in a discipline is a promising direction for organizing science instruction and curriculum across grades K-8. A research and development program is needed to identify and elaborate the progressions of learning and instruction that can support students' understanding of these core ideas. The difficult issue is deciding what to emphasize and what to eliminate. (NRC, 2007b, p. x)

The learning-progression approach to the design of curriculum, instruction, and assessment is grounded in domain-specific or core-knowledge theories of cognitive development and learning as documented in recent NRC reports (NRC, 1999, 2001, 2007b; Smith, Wiser, Anderson, & Krajcik, 2006). The emerging notion is for learning progressions at the K–8 grades to be built on 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, 2007b).

Learning progressions would be designed to also take up epistemic and social goals of science through the teaching of scientific practices, such as measurement, argumentation, explanation, model building, and debate and decision making. Critically important for the children's development of science learning, as discussed above, are the appropriation of criteria for assessing and evaluating

- the status of knowledge claims,
- the status of investigative methods,
- the tools of measurement, and
- the status of representations and audience for communicating ideas and information.

This list represents a sample of elements in the "mangle of practice" for school science. Recall that the *TSTS*'s third and fourth strands of scientific proficiency, respectively, are "Understand the nature and development of scientific knowledge" and "Participate productively in scientific practices and discourse." In other words, the development of epistemic discourse practices is central to learning within learning progressions. But this raises yet again the important issue regarding details or the grain size of information and ideas we ask children to consider. Clearly judging students' ideas as right or wrong does not provide valuable feedback to learners. Formative assessment strategies that seek to make thinking visible are most effective when the appropriate level of details is designed into tasks such that knowledge deepens, reasoning develops, and learning progresses. Within science education, an important issue is the level of detail needed to develop epistemic reasoning. Consider, for example, the various frameworks used to guide and promote argumentation discourse in classroom learning environments and computer-supported classroom learning.

The adoption and development of argumentation frameworks has gained in importance in the past two decades. Jimenez-Aleixandre and Erduran (2007), in the opening chapter of their edited volume on argumentation research in the science classroom (Erduran and Jimenez-Aleixandre, 2007), propose five potential contributions the introduction of argumentation can have on science learning environments. First is supporting access to cognitive and metacognitive reasoning. Second is supporting the development of communication and critical thinking. Third is supporting the development of scientific literacy and enabling students to engage in the language of science. Fourth is supporting participation in practices of scientific culture and developing epistemic criteria to evaluate knowledge. Fifth is supporting the growth of reasoning employing rational criteria. Employing argumentation practices along any one of these five dimensions requires contexts and levels of detail that make such outcomes of argumentation possible, let alone successful.

When looking across the various available options for argumentation frameworks, one sees that there are issues regarding the grain size of information being sought and used (Duschl & Osborne, 2002; Kelly, 2007; Sampson & Clark, 2006). Toulmin (1958), for example, distinguished between field-dependent and field-independent forms of argumentation, with the latter focusing on the general patterns of arguments involving claims, warrants, backings, rebuttals, qualifiers, and conclusions. Perelman and Olbrechts-Tyteca (1958/1969) maintain that argumentation is fundamentally rhetorical in nature, focusing as it does on persuasion. Walton (1996) advocates that argumentation be seen as a dialectical process guided by informal logic, because considerations for goals, intents, values, and audiences creep into the process. Jimenez-Aleixandre and Erduran (2007), using Darwin's "one long argument" *On the Origin of Species* as a context, describe several aspects of argumentation. Arguments provide evidence for the justification of knowledge. Arguments bring about convergence of lines of reasoning and theoretical frameworks. Arguments seek to convince audiences. Arguments can be seen as debates between two parties or two competing theses. As their edited volume demonstrates, there is a wide variety of frameworks employed in science classrooms. The question asked by Sampson and Clark (2006) in a review of five different frameworks for examining rhetorical argumentation is "How does any framework inform us about the quality of students' argumentation?"

Argumentation, although common among many cultures and communities, when played out in science, has particular *what counts* rules for knowledge building. Such knowledge-building rules represent the epistemic demands (Sampson & Clark, 2006), epistemic resources (Hammer & Elby, 2003), epistemic actions (Pontecorvo & Girardet, 1993), and the practices of epistemic communities (Duschl & Grandy, 2007). Thus, as stated above, when thinking about argumentation discourse in classrooms, there is a need to have tools that can support and scaffold students' participation in argumentation discourse and, importantly, teachers' assessment of the students' argumentation to guide its development.

Sampson and Clark (2006) review five frameworks used for the assessment of argument:

- Toulmin's (1958) argument pattern in science education research (Jimenez-Aleixandre, Rodriguez, & Duschl, 2000; Kelly, Druker, & Chen, 1998; Osborne, Erduran & Simon, 2004),
- Zohar and Nemet's (2002) modification of Toulmin,
- Kelly and Takao's (2002; Takao & Kelly, 2003) framework examining the epistemic status of propositions,
- Sandoval's (2003; Sandoval & Millwood, 2005) framework for examining the conceptual and epistemic quality of arguments, and
- Lawson's (2003) framework for examining the hypothetic-deductive validity of arguments.

The focus of the review was "(a) illustrating the logic and assumptions that have pervaded research in the field, (b) summarizing the constraints and affordances of these different approaches, and (c) making recommendations for new directions" (Sampson & Clark, 2006, p. 655). The analyses were conducted with lenses examining the epistemological criteria used by each of the five frameworks. What Sampson and Clark (2006) report is that the extant frameworks do not get down to a precise level of epistemic criteria:

> Unfortunately . . . the majority of the analytical methods that have been developed to assess and characterize the nature of the rhetorical arguments . . . have provided very little information about how the rhetorical arguments generated by students reflect these criteria. (p. 659)

Adoption of argumentation frameworks for use in classrooms does indeed have potential to shape the epistemic and social practices of students. Kelly (2007) makes an important cautionary point, though, about classroom discourse practices. He argues that norms of interaction that permit close examination of evidence while preserving pupils' dignity are not well understood. Pointing to the social nature of science epistemology, Kelly goes on to state that epistemic criteria are the accepted norms for justifying and evaluating knowledge among a given community. Making that community a K–12 classroom opens up a broad range of issues about social engagements and the content of those engagements. Following Longino's (2002) social norms for social knowledge scheme, Kelly offers up some suggestions for making science classrooms places where dialectical discourse interactions like argumentation can occur:

- A need for venues and for public discussion and corrections among members.
- A need for uptake of criticism, tolerance for dissent and changing views, but such levels of disagreement may pose problems if left unresolved.
- A need for public standards that would change with relevant criticism and as the inquiring community changes goals and values.
- A need for intellectual authority; teachers' authority needs to be tempered to support open discussions; students' experiences with shared authority can lead to confidence, responsibility, and understanding of cognitive goals of science.

Changing the nature of classroom discourse practices has implications for teachers as well, naturally. A position taken by Osborne et al. (2004) and Erduran, Simon, and Osborne (2004) is that teacher comfort is a justification for using a generic use-of-rebuttal framework that can define levels of engagement and function across science domains. Although there are merits in this position regarding teachers' comfort with the basics of managing a classroom that promotes scientific argumentation discourse, there remains concerns about the quality of argumentation and reasoning that can emerge if more refined epistemic criteria are not introduced to students.

Shifting the focus of learning from *what* to *how* and *why* requires new forms of knowledge to be brought to the classroom conversations. Consider the proficiency of "Understand the nature and development of scientific knowledge." What is the appropriate level of detail or grain size of information to consider? To begin addressing this important issue, let us revisit the idea that philosophers of science have traditionally drawn a distinction between (a) the context of generation and discovery where new ideas, methods, and questions emerge and (b) the context of justification where ideas, methods, and hypotheses are tested against the prevailing evidence and tested for coherence with prevailing beliefs. Contemporary practices in science education reflect this endpoint perspective on nature and development of science.

What we have learned in the science studies as well as in the learning sciences is that a consideration only for the endpoints of generation and justification is not the proper scientific game nor is it the appropriate game of science education. What research suggests is the proper game for understanding the nature and development of scientific knowledge is engagement with the ongoing pursuit and refinement of methods, evidence, and explanations and the subsequent handing of anomalies that are a critical component of proposing and evaluating scientific models and theories. In other words, dialogical processes characterize science-in-the making approaches and the epistemic and social dynamics that seek to fill in the details between the initial and important context of generation scientific activities and the concluding and necessary context of justification activities.

The epistemic and social dynamics, though, bring new and important practices to bear for learning environments. Key among them is the need for establishing dialogic or dialectical learning environments that facilitate two important activities. One is making students' thinking visible and doing so within a given conceptually grounded learning context that by design promotes the attainment of scientific reasoning and the motivation to learn. The other is enabling dynamic assessments of learning that provide feedback to learners on the conceptual, epistemic, and social dimensions of engaging in science and science education. The focus needs to be on both inquiry practices and on literacy practices. The inquiry practices address the middle ground between the generation and justification endpoints and include such things as obtaining and using measurements, data, evidence, models, anomalies, and explanations. The literacy practices address the communication and representation activities of science, activities that embrace, among other things, mathematics, reading and writing, argumentation, modeling, measurement, and representation.

Once again, though, we are confronted with the issue of grain size and norms of interaction. What is the appropriate level of detail needed in the middle-ground discourse between generation and justification? What is the appropriate level of detail to assume for students' science learning? Should the level of detail be fixed and static, or should it be dynamic, deepening with students' and teachers' level of expertise and experiences? These are but some of the important research questions that we face regarding the coherent infusion of learning science and science studies into K–12 science education.

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