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Rigor and Equity by Design: Locating a Set of Core Teaching Practices for the Science Education Community

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Introduction

Responsible scholarship on teaching has always portrayed the relationship between instruction and student learning as both uncertain and problematic. The past fifteen years of research in science education can be summed up in terms of that relationship: We now have substantial evidence that young learners are capable of far more sophisticated forms of reasoning and science activity than previously thought, if provided sufficient time for learning and strategic types of support; however, we also know that the conditions necessary for such learning are fundamentally different from those found in most science classrooms today. Conditions for learning are shaped by a number of factors, including the quality of the curriculum, class size, the amount of time devoted to science instruction each week, access to material resources in the classroom, and, increasingly, the influences of routine testing. None of these, however, have as direct an influence on children's academic futures as the kinds of teaching practices that shape their everyday interactions with subject matter and with other learners (Cochran-Smith, 2003; Darling-Hammond, 1997). The ways in which science teachers work with students and their ideas mediate opportunities to learn more powerfully than any other part of the schooling ecology.

In this chapter we use observations from a variety of research fields to better understand the divide between students' potential for engaging with science and what they are currently asked to do in classrooms. We treat the larger context of this situation as dynamic. The subject matter of science is itself in flux, both in terms of the expanding knowledge base of the discipline and in terms of new conceptions about how scientists construct this knowledge over time. We are also learning more each year about the capacity of students to think about abstract ideas, pose scientific questions, design and enact investigations, argue with evidence, and monitor their own intellectual progress. And finally, the very makeup of student populations is shifting dramatically as classrooms become increasingly diverse. All of these changes have implications for the work of science teaching and for how we define expertise in the profession. These changes also have the potential to widen the current gaps in achievement between well-served and underserved populations of students.

To furnish a generative context for conversations in this chapter about advances in professional practice and student learning, we use the construct of ambitious teaching. This type of teaching aims to support all students in engaging deeply with science in equitable and rigorous ways. This involves opportunities to reason about key subject matter ideas, participate in the discourses of the discipline, and solve authentic problems (Fennema, Franke, Carpenter, & Carey, 1993; Hill, Rowan, & Ball, 2005; Lampert & Graziani, 2009; C. Lee, 2007; Newmann & Associates, 1996; Rosebery, Ogonowski, DiSchino, & Warren, 2010; Wells, 2000). Although there are numerous examples of ambitious teaching in various subject matter literatures, the idea is still a work in progress. What binds successful cases together, in addition to their focus on rigor and equity, are two working assumptions: (1) the quality of teaching is assessed by examining the participation and learning of all students in the classroom rather than by the completion of a curriculum or by standardized test scores; and (2) widespread and sustainable improvements in teaching will require a repertoire of practices that can influence student learning and can be refined over time by both practitioners and researchers. Such practices have been referred to as "core" to the work of teaching (Ball, Sleep, Boerst, & Bass, 2009; Franke & Chan, 2007; Hatch & Grossman, 2009).

Ambitious teaching, then, embodies a challenge that would integrate researcher knowledge, practitioner experience, and new institutional structures for pedagogical experimentation. At the same time, it represents an achievable ideal whose realization depends on innovations drawn from a diverse array of research fields. This chapter, then, is an extended thought experiment in which hypotheses about forms of science teaching—some that do not exist in common practice—are developed, using recent research as a platform for projecting what "could be" in the near future.

Structure of This Chapter

This chapter is divided into three sections. In the first, we present a set of assertions about the current state of science reform and the need for a more coherent vision of instructional excellence that can support learning for all students. We cite the disconnects between the pedagogically conservative forms of teaching that our educational system now supports, and the impressive capabilities of young learners to engage in the reasoning and activities of the discipline. We argue here that issues of equity should be fundamental to conversations about reform, and that concerns in particular for the rigor of instruction should not be separate from the concerns to provide all students with opportunities to learn science.

In the second section, we describe how recent bodies of scholarship have begun to reshape what we think is pedagogically possible and effective for learners in science classrooms. For example, more authentic images of how scientists work together to construct knowledge are coming to light, and many of these ideas are already being reflected in current reform documents. Findings from programs of research on learning are now challenging long-standing beliefs about the limitations of young students in reasoning about science ideas and in participating in the discourses of science. These studies are important to the conversation about teaching because, as a group, they begin to redefine conditions of instructional support that are necessary to realize ambitious goals for student learning.

As part of this section we consider how culture and the context of schooling have shaped what we understand young people are capable of in science, challenging stereotypes about learning and engagement in science. These studies provide insights into the ways in which students come to our classrooms—with rich and varied sense-making repertoires—many of which have not been legitimized in schools. It is important for teachers to notice and leverage these repertoires in ways that provide a rich context for students' scientific work with peers. We also consider the insights that studies on identity and learning provide for framing equity issues in ambitious teaching.

In the third section of this chapter, we draw from advances described in the first two sections to propose a practice-based vision of ambitious teaching. We begin by describing how the researcher community and the teacher community might think about the idea of "practice" in order to clarify what the object of professional improvement is and to support analyses of how practice might be refined over time. We then propose sets of practices that embody recommendations from the various research literatures for teaching, for the design of instruction, and for student learning. These practices, we argue, appear to be integral to a vision of ambitious instruction. The purpose of presenting these, however, is not to claim that they define some ideal form of teaching, but to demonstrate how important practices might be characterized by researchers and practitioners as objects of study, testing, refinement, and productive variation. The ultimate goal is to develop a rich and varied array of important practices that both communities would consider the heart of effective teaching. Such a vision is instrumental for the continued improvement of teaching by individuals and by the community.

Science as Practice and Teaching as Practice

Throughout these chapter sections we draw upon various literatures to develop practice-based views of teaching and of science itself. In both conceptions we refer to the essential activities that members of a field are socialized into as part of their professional training (Bourdieu, 1977; Reckwitz, 2002). *Scientific practices* that are relevant to school learning include activities such as designing investigations, developing explanations, and arguing from evidence. Based on recent scholarship, viewing science as engagement in practice is a more authentic alternative to the common notion of "science as the accumulation of knowledge." Even more important, numerous classroom studies show how students' reasoning about concepts is supported by opportunities to participate in science practices, such as theorizing about natural phenomena, comparing and contrasting explanations with peers, and testing and revising models.

By *teaching practices* we mean the recurring professional work devoted to planning, enacting, and reflecting on instruction. We emphasize teaching as practice as a way to acknowledge that student participation and learning are mediated most directly by teacher decisions about the kinds of tasks, talk, and tools used in the classroom. Without some common framework to describe and guide good teaching—as practice—it is difficult for either researchers or practitioners to communicate about meaningful classroom problems, and it is especially difficult for professional knowledge to be shared, tested, and refined over time.

How Rigor and Equity Will Be Framed in This Chapter

Rigor and equity characterize ambitious teaching. Rigorous work presses learners to go beyond their current levels of understanding or their current ability to participate in the discourse and activities of science—but rigor is not simply "challenging work" as laid out in a lesson plan nor is it only a set of expectations for performance. We describe rigor as a characteristic of the interactions between learners and those responsible for supporting learning. In this view, rigor is codetermined by standards of performance particular to a task, the quality of support offered by the teacher, and the intellectual activity engaged in by learners. Rigor depends upon on all three of these conditions working together.

Equity in this chapter is described from the perspective of teaching practices. In broad strokes, equity in classroom instruction means providing opportunities for *all* students to learn challenging ideas, to participate in the characteristic activities of the discipline, and to be valued as important and fully human members of the science learning community. For the work of teaching, this typically requires (but isn't restricted to) using specialized forms of scaffolding for reading and writing, providing participation structures for learners to interact with others around intellectual work, modeling language use and science practices, making explicit how the practices of science are culturally and historically grounded, adapting tasks, supporting productive science identity work, and using students' current ideas, experiences, and language as intellectually generative resources for the learning of everyone in the classroom. These opportunities are sometimes made available to an entire class; at other times, they are tailored or differentiated to meet the needs of particular students.

Conversations about equity and instruction must acknowledge that poverty has a wide range of effects on teaching and on children's futures. Students in poverty-affected schools are more likely to have inexperienced or underqualified teachers. Schools affected by poverty are also likely to have fewer demanding college preparatory courses, more remedial courses, and higher teacher turnover (Alliance for Excellent Education, 2008; Darling-Hammond & Post, 2000; C. Lee, 2004). Both novice and experienced teachers appear to be drawn to schools with low concentrations of poverty, low populations of minorities, and high levels of student achievement (Boyd, Lankford, Loeb, & Wyckoff, 2005). The point is that the success of broad-scale attempts to elevate the practice of teachers will rely on policy changes that improve the institutional landscape in which educators and students strive to succeed.

Selection of Research for This Chapter

The conversations in this chapter are composed of a number of conceptual threads that contribute to our understanding of rigorous and equitable teaching and how it might become common rather than exceptional. We have selected programs of scholarship, both conceptual and empirical, and high-quality individual studies that have shaped the field's thinking about the work of science teaching. Advances in how we think about teaching should be informed by fields outside as well as within science education. Noticeably, some bodies of science education research remain insular and do not take advantage of sophisticated works from, for example, mathematics education, child development, or teacher learning, which could expand our thinking. In this chapter we draw upon a number of studies in areas outside science education because the novel ways in which ideas are developed and used in these fields can inform projects of importance in our own research community. On the other side of the coin, there is, regrettably, much exemplary work within the field of science education writ large that does not appear here. This omission is not a reflection of the quality of such studies, but rather of their applicability to a theoretically focused account of advancing science teaching practice in our schools. We do not, for example, directly explore the roles of technology, curriculum development, summative forms of assessment, or professional development. Those interested in deeper treatments of ideas not emphasized here may refer to other chapters in this volume or other handbooks dedicated to science education.

Why We Need a New Vision for Science Teaching and Learning

We now outline three assertions that form the basis for a larger conversation about the advancement of science teaching and learning. These claims are informed by recently developed theoretical stances about learning, shifts in student demography, and studies of contemporary classroom practice.

1. What we know of how children learn and what they are capable of in the science classroom now outstrips current models of instruction.

Over the past twenty years, several research programs have documented instructional conditions that engage learners with science ideas in productive ways, allowing them to, for example, construct and test theoretical models of natural phenomena, design controlled experiments, create novel ways of representing variability in data, or argue convincingly with evidence (see, e.g., Lehrer & Schauble, 2004; Magnusson & Palincsar, 2005; K. Metz, 2004; C. L. Smith, Maclin, Houghton, & Hennessey, 2000)—we refer here to elementary school students, some as young as 7 or 8, who are engaged in reasoning and in epistemic discourses that many college students would find unfamiliar. The instructional environments that support these remarkable post-Piagetian, postconstructivist outcomes are the products of intensive design efforts by university researchers, content experts, and teachers, whose contributions have been critical in shaping this work.

Because we now have a better sense of what students are capable of, a gap is emerging between new expectations for learning and how science is currently taught (including expectations built into resources such as state standards, curricula, textbooks, assessments, etc.). Although there are many individual classrooms in which children are routinely engaged in challenging and well-supported science learning, the broader picture of practice is less positive. Several large-scale observational studies indicate that classroom science learning for students remains intellectually undemanding and procedural, and it is often disconnected from the development of substantive science ideas (Abrahams & Reiss, 2012; Corcoran & Gerry, 2011; Pasley, 2002; K. Roth & Garnier, 2007; Weiss, Pasley, Smith, Banilower, & Heck, 2003). The aspects of instruction known to support engagement and learning—such as maintaining an environment of high expectations, responding to student thinking, and linking activity with science ideas and with the out-of-school experiences of young learners—are precisely where classroom teaching appears weakest. Several interrelated themes are evident across all studies in which teaching has been directly observed:

> We are using research here to characterize teach*ing* rather than teach*ers*. The distinction is that teaching is a culturally and historically shaped activity (Cole, 2010), and that individual teacher practice occurs within and as a result of multilayered systems of institutional priorities, policies aimed at accountability, and varied forms of support or lack thereof for particular practices (Elmore, 2000). When trends in teacher practice occur with regularity across multiple studies and sites, we should consider influences beyond the individual, such as teacher preparation, the national focus on high-stakes testing, the quality of professional development opportunities, the availability of adequate teaching materials, such as curricula or textbooks, and the relative emphasis placed on science learning in schools, for example, whether educators can be punished for lack of student progress in areas other than science.

a. The classroom environment for learning is moderately well organized and characterized by a generally positive, respectful climate.

b. Although students frequently engage in "active work," it is often procedural and does not involve authentic forms of scientific practice or reasoning.

c. Far too few teachers, particularly in U.S. classrooms, help students link activity to substantive science ideas.

d. Teacher questioning and tasks in general do not demand much from students intellectually; instruction is frequently aimed at the recall and reproduction of textbook explanations.

e. There are rarely "big picture" science ideas for students to develop understandings of, or for teachers to organize units around.

To get a sense of both trends and details about the state of instruction, we refer to studies that are based on direct observation of teaching or on video analysis of classroom instruction. A study titled "Looking Inside the Classroom" used a nationally representative sample of 31 middle schools in the United States (Weiss et al., 2003) to assess dimensions of practice, such as engaging students, creating environments conducive to learning, and helping students make sense of science content. One set of measures assessed whether science was treated as a dynamic discipline, with student opportunities for conjecture, investigation, theorizing, and application. In more than 60% of classroom observations, they found no attempts by teachers to portray science as an evolving body of knowledge. The majority of lessons, especially those intended to provide review for high-stakes tests, treated science as a collection of known facts and procedures. Similar observations were reported from the TIMSS (Third International Mathematics and Science Study) video analyses in which a random sample of 100 eighth-grade classroom lessons were recorded in each of five countries (K. Roth et al., 2006). Students in all countries, including the United States, were more likely to observe phenomena during independent practical activity than they were to construct models or conduct experiments.

These studies also assessed opportunities for students to make sense of science activities. Prevalent across middle school grade levels in the "Looking Inside the Classroom" study (Weiss et al., 2003) were lessons in which students experienced activities, worked on problems or exercises, or attended to presented information, but never had a chance to distinguish important concepts from minutiae or to connect new information to existing knowledge. The authors reported, "Teachers seem to assume that the students will be able on their own to distinguish the big ideas from the supporting details in their lectures, and to understand the [science] ideas underlying their computations, problem-solving, and laboratory investigations" (p. 71). Similar findings in U.K. primary and secondary schools were reported by Abrahams and Reiss (2012). In the TIMSS study, eighth-grade students in higher achieving countries typically concluded practical activities by discussing the results and drawing conclusions, but for students in the United States, this was the rare exception for science lessons. The trend in U.S. classrooms of "activity without understanding" has been identified in other studies as well (see, e.g., Corcoran & Gerry, 2011).

All the higher achieving TIMSS countries had strategies for engaging students with important science ideas. In the United States, however, content played a less central role and sometimes no role at all in science lessons. Instead, instruction was usually built around involving students in a variety of activities, such as games, puzzles, humor, dramatic demonstrations, or outdoor excursions (K. Roth & Garnier, 2007). Unlike the teachers in Australia and Japan, U.S. teachers did not typically use these activities to support the development of science ideas. K. Roth et al. (2006) noted that when teachers did present science content, they more commonly organized it as a collection of discrete facts, definitions, and algorithms rather than as a connected set of ideas. The lack of connection between activity and ideas exists even in U.S. schools that have received extensive support through professional development. For example, case studies conducted by principal investigators of 10 local systemic change initiatives at the K–8 and 6–12 grade levels revealed familiar weaknesses in participating teachers' instruction (Pasley, 2002). Classroom observations documented "mechanical" implementation of instructional materials and only infrequent use of higher level questioning strategies or reasoning with data that students had collected in their investigations.

Systematic sense making, of course, cannot happen without verbal prompts from teachers or varied opportunities for student talk. In the Weiss et al. (2003) study, the authors examined teacher questioning and discourse in general. In their analyses, fewer than one in five lessons incorporated questioning that was likely to move student understanding forward (i.e., finding out what students know, pressing for reasoning, encouraging students' self-monitoring of their own thinking)—even when the rest of the lesson was otherwise well designed. There were many instances cited of teachers asking low cognitive demand, "fill-in-the-blank" questions in rapid-fire sequence, with the focus on correct responses (often single words or phrases) rather than on student understanding. The authors concluded that questioning was "among the weakest elements of [science] instruction" (p. 71). These fi ndings are similar to those by Bowes and Banilower (2004), who analyzed lessons from elementary school, middle school, and high school classrooms where teachers had been supported for years through well-funded professional development initiatives. Their data showed that fewer than half of the lessons, even those of teachers who received significant training, were likely to be rated as adequate in the areas of questioning and sense-making opportunities.

Not all aspects of instruction were found to constrain students' engagement. A case in point comes from a large school district in the eastern United States, which included data from observations of 55 elementary school classrooms, 37 middle school science classrooms, and 29 high school science classrooms (Corcoran & Gerry, 2011). These observations were conducted by teams of evaluators using rubrics aligned with reform-based teaching. The broad trends that held across all grade bands were that teacher-controlled factors that *did not directly involve intellectual transactions with students* (classroom organization, fostering positive classroom climate, and having clear learning goals) were rated more positively than practices that required teachers to organize students for talk and work with disciplinary ideas. Fewer than one third of observations at the elementary school, middle school, and high school levels showed students engaged in any type of higher order thinking. Qualitative reports of these classrooms indicated that, although the lessons seemed well organized, students were often disengaged and that didacticism dominated instruction. Weiss et al. (2003) also found that middle school teachers in their study generally allowed students' ideas to be voiced and that they welcomed questions about science from students. This analysis, however, did not indicate whether or how teachers might have used these contributions as resources in constructing more meaningful or robust science knowledge for the whole class.

The instructional trends described here are not unique to U.S. classrooms. In a report on science teaching in Europe, Osborne and Dillon (2008) characterize the pedagogy using a conduit metaphor in which knowledge is treated as a commodity to be transmitted to students (see also Lyons, 2006; Osborne & Collins, 2001). The discourse in many European classrooms follows an "I-R-E" pattern: the teacher asks a question (initiation), the student provides a short answer (response), which is then followed by a statement of its correctness by the teacher (evaluation). The authors of the report add that in these classrooms, "little of the writing in school science transcends the copying of information from the board to the notebook. It is rare, for instance, to see any collaborative writing or work that involves the construction of an argument" (Osborne & Dillon, p. 9). Little opportunity is provided for students to use the language of science, even though there is substantial evidence that opportunities for hypothesizing, explanation, and argument lead to enhanced conceptual understanding (Mercer, Dawes, Wegerif, & Sams, 2004; Zohar & Nemet, 2002). In Australia the science experience for students becomes less relevant to them and less engaging as they move through the school system; after the elementary grades, the focus of instruction shifts toward listening to teacher-centered presentations, copying notes, and "cookbook" activities (Goodrum, Hackling, & Rennie, 2000).

The practices described so far unquestionably influence students' opportunities to learn science, and they themselves are influenced by the professional arrangements in schools and by policy. For example, a national survey of teachers intended to track changes in such factors between 1993 and 2000 (P. S. Smith, Banilower, McMahon, & Weiss, 2002) found science educators in every grade band reported a diminished amount of decision making related to curriculum. A more recent survey by Banilower et al. (2013) indicates that less than 25% of elementary school and middle school teachers feel they have strong control over course goals and selection of content. Teachers at all levels were much more likely in 2000 than in 1993 to agree that the testing program in their state or district dictates what they teach. Even more striking was the lack of opportunity to observe colleagues teaching. In 1993 only 11% of teachers in grades one–four and five–eight agreed or strongly agreed with the statement "Science teachers in this school regularly observe each other teaching classes as a part of sharing and improving instructional strategies." By 2000 even these meager numbers had fallen: A mere 4% of teachers in grades one–four and 5% of teachers in grades five–eight agreed or strongly agreed with the statement. Only one in four teachers had time during the week to collaborate with colleagues in their schools, and even these discussions were not devoted to decisions about curriculum.

Some school and district arrangements do not provide access to the materials and expertise that support teaching (Banilower et al., 2013). In a study of elementary school science teaching across the state of California, Dorph., Shields, Tiffany-Morales, Hartry, & McCaffrey (2011) cited multiple issues affecting the amount and quality of science teaching: the elimination of lead science teachers; the reassignment of many teachers to different grade levels as a result of reductions in staff; the late arrival of science modules at the schools and premature pickup of these modules from the schools; the lack of science textbooks or supporting materials; and the heavy emphasis on improving student achievement in areas of focus on the state assessment, namely, literacy and mathematics (p. 12). Taken as a whole, these conditions limit effective science teaching (or any teaching) and confound attempts to improve practice over time.

The patterns of practice described in this section are undoubtedly influenced by systems beyond the control of the teacher. But some of the forces shaping the very grammar of schooling today originate in industrial views of teaching and learning, which developed early in the 20th century. The goal then was to ensure standardization—all students were to master the same curriculum in the same way. When this model emerged nearly 100 years ago, little was understood about how people learn. As a result, schooling was based on a number of commonsense assumptions about knowledge, understanding, and instruction that had never been tested scientifically. The design of curricula was likewise uninformed by a study of how children learned, and was instead based on intuitive principles by "expert adults," such as mathematicians, scientists, or historians (Sawyer, 2008). For example, it was believed that knowledge is a collection of facts about the world and procedures for how to solve problems; that the teacher's job is to transmit these facts and procedures to students; and that simpler facts and procedures, often referred to as "the basics," should be learned first, followed later at some undefined time by more complex ideas.

This perspective has been called *instructionism* (Papert, 1993) or the *transmission and acquisition* model of schooling (see Rogoff, 1990), because it suggests that the focus of the teacher is to organize activity and communicate information, and that learners then reproduce explanations, facts, and procedures. Instructionism is outmoded, even archaic, as a guide for teaching today. But ample data suggest that these intellectually conservative assumptions are still in use. In fact, evidence indicates that instructionism, with its "teacher-dominated discourse, textbook-based lessons, and coverage as the main curricular principle" (Sykes, Bird, & Kennedy, 2010, p. 465) remains the dominant, albeit implicit, theory underlying science teaching in most countries (Osborne & Dillon, 2008), providing the illusion of rigor while largely ignoring equity. Although some might point to changes brought on by the science inquiry or active learning movements of the past 30 years, the rich disciplinary work that students were intended to participate in is often reshaped in classrooms as rote procedures or skills that have been artificially separated from the conceptual and epistemic conversations that motivate and give meaning to the activity itself (Duschl, 2008; National Research Council [NRC], 2012). This seems logical, given that the current conditions of science teaching and the inherited cultural images of the work of educators influence pedagogical decisions and the everyday opportunities that our children have to learn about the natural world.

2. Supports for the continual advancement of teaching should be predicated on a clear vision of practice that improves learning—a vision that does not yet exist.

Since the turn of the 21st century, the idea of reforming teaching has been supported by multiple areas of research, including science studies, research on learning, epistemology, and instructional design (National Research Council [NRC], 2007). The intent of reform teaching is clear—the way it has been represented, however, has not always been in terms of actionable, principled practices (Marx, 2012). Rather, it has been portrayed in terms of what students will be able to do as a result of instructional design. For example, descriptions of reform teaching include opportunities for students to find solutions to authentic problems by asking and refining questions, designing and conducting investigations, gathering and analyzing data, making interpretations, and drawing conclusions (National Research Council [NRC], 2000, 2005). The teacher's role, which is not articulated, is presumably to press students to explain, critique, and revise their ideas as they explore phenomena. These descriptions only suggest what teachers should be able to do; they tell us little about the fundamental skills and understanding required to foster such valuable kinds of student performance.

The recent volumes of *Taking Science to School* (NRC, 2007) and the *Framework for K–12 Science Education* (NRC, 2012) make notable steps forward in translating research on science, science teaching, and learning into a set of recommendations about goals for instruction, the design of curriculum, and meaningful forms of assessment. But without sustained public conversations about specific forms of teacher practice, instruction may continue to be guided instead by conceptually vague approaches (hands-on/minds-on), theory (constructivism), scripts (curriculum kits), simplistic models of disciplinary activity (the scientific method), or slogans ("Kids need the basics"). Lacking a clear vision of highly effective teaching, most new policies aimed at changing practice are inevitably reshaped by various stakeholders to accommodate how science is already taught, making reform unrecognizable in the classroom (Elmore, 2000; Spillane & Jennings, 1997).

Not only do the preceding approaches fail to adequately define what a teacher must understand or do in classrooms, but they also carry no obvious responsibility for recognizing diversity in classrooms, using students' ideas as resources for instruction, scaffolding students from nondominant groups to participate in discourse and activity, or allowing meaningful assessments of understanding. These approaches are often translated into unproblematic routines in teacher education or professional development settings. The routines can be largely procedural ("going through a lab activity together," "writing a lesson plan," or "introducing an idea"), with little attention paid to the conceptual, interpersonal, or epistemic work that students should be doing in a science classroom. In contrast, principled practices, especially those that are core to the work of teaching, would be productively problematic because they would respond to the reasoning and activity of children, whose understandings of the natural world are always assumed to be partial, fluid, and shaped through social interaction.

This in turn prompts questions about the literature on the nature of professional expertise. What recognizable combination of teaching practices do accomplished educators use to engage learners? Do these practices make science accessible to students who are difficult to engage, who think in creative ways, or who bring different palettes of cultural experience to the conversation? In light of these questions, "expert" teaching performances would require new kinds of evidentiary warrants from classroom studies that clearly demonstrate broader student participation and learning.

Given that teaching directly mediates students' opportunities to learn in the classroom, it is surprising that there are no commonly acknowledged practices, linked with student learning or increased participation in the intellectual work of the classroom, that would be considered essential to the professional repertoire of science educators. Sociologist of schooling Dan Lortie (1975) framed this problem, arguing that the lack of a technical core in teaching paved the way for educators to invent their own definitions of what works, based on individual experience or folklore, and that this might explain the "reflexive conservatism" that characterizes teaching in classrooms. If teaching that is both rigorous *and* equitable could be characterized in terms of definable practices, then groups of educators either within or across institutions could more easily engage in the continual and collective improvement of instruction. Based on this premise, Bryk (2009), for example, spells out a theory of action around the organization for professional learning within schools:

> Educators have a shared language about goals for students and understand how these align over time around some larger conception of student learning. Teachers also share a common evidence base about what constitutes learning. This allows them to analyze and refine the cause-and-effect logic that organizes their shared work. Finally, tying this all together is an explicit process for socializing new members into the community and for organizing ongoing social learning among all participants. (pp. 599–600)

This type of work is critical grounding for a science of performance improvement (Bryk, 2009; Cobb, Zhao, & Dean, 2009; Raudenbush, 2008), which in turn can inform an evidence-based system of learning opportunities, tools, and formative assessments—tailored to the needs of educators—that supports continuous progress toward effective and equitable classroom instruction. This conceptualization of professional learning disrupts the image of teachers working resolutely but alone to somehow "get better" at what they do in their classrooms. In the preferred view, teachers are professionals supported by collegial systems and socioprofessional routines—which teachers have a hand in shaping—to advance their learning and the learning of their students.

3. Research and practice should reflect our emerging understandings of the cultural dimensions of teaching and learning science.

Access to a high-quality science education is considered a civil right for all students (Tate, 2001). Science literacy opens doors to high-paying professions, provides a knowledge base for informed conversations with health care workers, educators, and business and community leaders, and helps demystify issues of global importance, such as air and water quality standards, population density, toxic dumping, and the economy. And yet there is abundant evidence that science education is mired in *inequality*.

Children with racial and ethnic minority backgrounds and from high- poverty neighborhoods in cities and rural communities disproportionately lack access to opportunities to learn science in meaningful ways. Schools have been complicit in the reproduction of the demographic trends of who has access to science and mathematics and who does not (Gilbert & Yerrick, 2001; Oakes, Joseph, & Muir, 2003). Although the on-ramps to science are monitored at the institutional level through tracking and course-taking pathways, barriers to participation exist in the ways classroom routines depict science as accessible only to "smart students" (Carlone, 2004), and as discontinuous with the ways of knowing and doing held by students with nondominant backgrounds (Bang & Medin, 2010; Warren, Ballenger, Ogonowski, Rosebery, & Hudicourt-Barnes, 2001).

Our review is also informed by the idea that science itself is human activity, shaped by history and culture. Although such a practice reflects culturally and historically organized ways of making sense of the world in Western society, the everyday work of scientists remains vastly diverse. The people, the tools, the social networks, the sense-making frameworks, and the practices that make up the work of scientists reflect a heterogeneity of inquiry that stands in stark contrast to the tendency in public discourse and schooling to equate it with a singular, unvarying set of methods.

When schools represent teaching and learning science as simply "knowledge acquisition" or "doing school," rather than scaffold participation in a community of practice in which canonical knowledge is only one valued outcome, students have few school-based opportunities to develop the kind of scientific literacies necessary for broader societal engagement. Such a focus on what students learn, to the exclusion of why or how they learn to participate in science-related communities of practice, obscures why many opt out of science, and why these trends noticeably manifest themselves along racial, ethnic, and socioeconomic lines.

Ambitious teaching, defined as engaging all learners with rigorous science in ways that value the diverse experiences the learners bring to the classroom, depends as much upon knowing who learners are and adapting instruction as it does on generalized principles for pedagogical planning. Our understanding of learners and learning in context has shifted dramatically in the past 25 years. In the chapter on science teaching in the third edition of the AERA *Handbook of Research on Teaching* (R. White & Tisher, 1986), the learner is described as someone who is capable of assimilating knowledge, and the outcome of learning is called "the new arrangement of memory" (p. 875). The probing of learners' understanding by researchers is just beginning (Driver & Easley, 1978). Students, although not treated as generic learners, are framed as containers for various attributes, abilities, attitudes, and preconceptions. Fifteen years later, the next *Handbook* edition suggests a more complex view of learners and learning, with attention given to how children think and how this is mediated by classroom contexts, that is, "teachers' and students' perceptions of the purpose of learning, interpersonal relations and patterns of power and control of behavior, balance between competition and cooperation" (R. White, 2001, p. 461). Still, learners are not yet portrayed as having lives outside the classroom. Normative images of science, of capable students, and of good teaching characterize the research (see Gage, 2009).

Since that time, the image of students has expanded, with more attention paid to the roles of culture and context. New theoretical lenses from fields such as social anthropology, linguistics, social psychology, and cultural studies have shifted attention from viewing the learner in purely cognitive terms to viewing the learner as immersed in interconnected social systems. Seen this way, learners have multiple identities, generated from both outside and inside schools (B. Brown, 2006; Brickhouse, Lowery, & Schultz, 2000; Calabrese Barton & Tan, 2009; Carlone, 2004). They often bring sophisticated social, linguistic, and intellectual repertoires to bear on the tasks of coping with school environments and tasks that may be incongruent with the demands of their everyday worlds (Gutierrez & Rogoff, 2003; O. Lee, 1999).

What is the relevance to ambitious teaching, then? The evolution of theory and research is creating more complex and sophisticated visions of "who the learner is" and "what counts as learning" in science classrooms. There is a moral as well as a pragmatic imperative to use research to understand how to take advantage of the expanded vision of diversity in science classrooms. The world and the children in schools are changing more rapidly than the fields of science teaching, curriculum design, educational technologies, and assessment can accommodate. Compelling advances have been made in these areas, but our theoretical understandings have not translated into widespread, reproducible, and principled teaching practices that shape everyday learning opportunities for children.

Summary

There is a gap between what children are capable of in the science classroom and what current science teaching affords them in terms of learning opportunities. We have argued that the researcher and practitioner communities cannot close this gap—that is, they cannot advance teaching—without sharing a clear vision of practice that improves learning and broadens student participation. The virtue in this proposed vision will not derive from its conceptual clarity or its close attention to how teachers interact with students around subject matter. Articulating what ambitious instruction might look like in terms of the tasks, talk, and tools involved is what can make rigor and equity more visible, and in the process more accessible, to those invested in the continual improvement of teaching.

Contemporary Scholarship That Is Reshaping Conversations

About Science Teaching and Learning

In this section we lay the groundwork for a repertoire of instructional practices that reflect ambitious teaching. We begin by describing the changes in what we know about the discipline of science itself, and how framing science as practice might allow teaching to better support students' reasoning and participation in activities authentic to science. We then link these ideas with the recent history of scholarship that has focused on the instructional conditions that support students' learning, and has caused us to reconsider expectations for young learners' development in science.

Science as a Discipline is Changing

Findings from science studies and the sociology of science. Ideally, science teaching invites learners to engage in activity and reasoning that are characteristic of the discipline (Schwab, 1978). What scientists do, however, and our understanding of it has changed dramatically in the past 30 years. The landscape of science now includes new fields of study—bioinformatics, physical cosmology, genomics, and supramolecular chemistry, for example—that blur the lines between traditional disciplinary specialties and use advanced technologies to explore previously inaccessible or inconceivable natural phenomena. Although these emerging domains provide exciting conceptual content for learners, equally important to education is an understanding of how contemporary science operates to advance new ideas. The field of *science studies* has provided insights here that inform how we think about "the work of science" in classrooms. Science studies is a group of disciplines drawing on the history and philosophy of science, anthropology, and the sociology of science, as well as cognitive psychology and science education, to understand better how knowledge of the natural world is refined over time.

One line of science studies that is reframing our ideas about authentic science for the classroom comes from investigations of how the social and material arrangements of laboratories and fieldwork influence the intellectual work done there (Knorr-Cetina, 1999; Latour & Woolgar, 1979; Pickering, 1995). This body of work corrects popular but inaccurate images of science, showing, for example, that scientific reasoning and theory development are not mentalist feats by uniquely gifted individuals working unaided and in isolation. Rather, this intellectual work is inseparable from a larger system of activity, which includes "networks of colleagues and institutions; specialized ways of talking and writing; the development of models to represent systems or phenomena; the making of predictive inferences; construction of appropriate instrumentation; and testing of hypotheses by experiments or observation" (NRC, 2012, p. 3-2). This science knowledge is the result of a dynamic cultural process of construction—a process which itself can change as science advances (Helmreich, 2009; Kuhn, 1970). What is important here for school science is that studies of scientists in action show that knowledge is not treated merely as an outcome of scientific practice. Rather, it is part of and developed through participation in practice itself.

Conceptualizing science as engagement in disciplinary practices. What kinds of practices do scientists engage in? Although there are many, two appear to be at the heart of disciplinary work—modeling and explanation. Different domains in science have their own questions, methods, and standards for evidence, but they are all engaged in the same core pursuit—the development of coherent and comprehensive explanations of the natural world. And often as part of that process, they use conceptual models to represent key ideas, reveal gaps in understanding, or test physical or computer models directly in order to generate data (Hempel, 1966; Kuhn, 1970; Longino, 1990; Nersessian, 2012). Controlled experimentation, which is often portrayed in curricula as the gold standard of science, is rarely used in some areas of inquiry (e.g., astronomy, meteorology, or field biology). All fields in science do collect data in a systematic way, but not all of them can manipulate the material conditions in which natural phenomena occur.

Broadly speaking, experimentation and the larger enterprise of inquiry are becoming routinely situated in model building, testing, and revising (Darden, 1991; Giere, 1988; Kitcher, 1993). Models take the forms of inscriptions (graphical or pictorial representations), analogies, physical constructions, or computer simulations (Giere; Latour, 1990). They can represent theoretical (abstract or conceptual) structures, such as energy pyramids in ecosystems, or those structures inaccessible to direct observation, such as the interior of the earth or long-term evolutionary processes. Regardless of how models are conceptualized, they generally emerge from some phenomenological context (event, question, or problem), and working with them involves identifying key features or attributes of the phenomenon and specifying how they are related (see Romberg, Carpenter, & Kwako, 2005). This is why many scientists treat models *as* explanations (Giere, 1988; Nersessian, 2005). During all stages of disciplinary work, these representations become central for the shared understanding of problems and ideas (Goodwin, 1994; Greeno & Hall, 1997).

Scientists are socialized into a number of practices (i.e., principled and goal-defined activity that marks membership in a community) that help them interact with each other in a coordinated way to inquire about and build knowledge. Pickering (1992) uses the notion of *science as practice* to highlight four mutually reinforcing dimensions of disciplinary work:

1. The *conceptual* dimension (the use of theory, principles, laws, and ideas as intellectual currency, i.e., objects to reason with and about).
2. The *social* dimension (the mutually agreed upon norms and language for developing, critiquing, and using ideas and resources with others).
3. The *epistemic* dimension (the philosophical basis for adjudicating how we know what we know, and why we are convinced we know it).
4. The *material* dimension (the designing of experiments and other observations; the creation and use of tools, technologies, inscriptions, and other resources to support intellectual work).

Each of these dimensions of practice influences and is influenced by the others—all are necessary to achieve the goals of science. Latour (1990) describes how scientists rely heavily on inscriptions (*material* representations) of data or the relationships among ideas (the working *conceptual* architecture) in order to mobilize the collective resources of their peers (through *socially* recognized routines) in the service of scientific explanation and argument (*epistemic* discourse) (see also Nersessian, 2012). This vision of science as practice reflects culturally and historically organized ways of knowing the natural world.

The interrelationships between the conceptual, social, epistemic, and material dimensions of the work are not merely authentic to the discipline. Numerous studies show how *students*' science reasoning is supported by and cannot be separated from structured opportunities to compare and contrast explanations with peers (Duschl & Duncan, 2009; Herrenkohl & Guerra, 1998; Radinsky, Oliva, & Alamar, 2010), opportunities to argue from evidence and evaluate the quality and reliability of various forms of evidence (Chinn et al., 2008; Sandoval & Millwood, 2005), and opportunities to invent and use specialized tools for collecting and representing ideas (Danish & Enyedy, 2006; Lehrer & Schauble, 2004). Each of these studies produced special resources for students or activity structures that leveraged interactions *between two or more of these dimensions* of science practice to support robust forms of student learning. These four dimensions should be attended to not only as individual ends in themselves, but also as interacting components of science instruction that catalyze learning.

Understanding a science-as-practice approach for teaching implies that learners are part of a cultural community that uses conceptual, social, epistemic, and material means to achieve valued goals (Duschl, 2008; Gee & Green, 1998; Lemke, 1990). These goals were articulated by the National Research Council (NRC) in its recent consensus publication *Taking Science to School* (2007) and incorporated into the *Framework* document for the Next Generation Science Standards (NRC, 2012). Students should be able to meet the following goals:

- understand, use, and interpret scientific explanations of the natural world
- generate and evaluate scientific evidence and explanations
- understand the nature and development of scientific knowledge
- participate productively in scientific practices and discourse (p. 334)

When a student achieves these goals, it is not merely an individual accomplishment. It also reflects that student's increasing capacity to participate with others in the range of activities that define membership in a science community (Rogoff, 1990). Lave and Wenger (1998) describe this as a person being "transformed into a practitioner, a newcomer becoming an old-timer, whose changing knowledge, skill, and discourse are part of a developing identity" (p.104).

This vision of learning is different from the individualistic knowledge acquisition perspective that pervades modern schooling. But the most useful understanding of how students learn about the natural world is an integration of these socially situated perspectives with the foundational work in individual cognition begun in the 1970s and the related theory, which explains processes such as self-regulation and higher order thinking. In upcoming sections, for example, the roles of metacognition, self-assessment, activating prior knowledge, and self-explanation are integral to studies of learning and the design of learning activity.

Implications for rigor and equity. Learning science from a discipline-based perspective is more than accumulating ideas about the natural world. Students work with a set of knowledge-building practices that are valued by a professional community. From a rigor standpoint, this means that students are asked to do more than comprehend ideas of others. They also construct new and deeper understandings by testing and revising claims, interacting with the ideas and puzzlements of other learners, figuring out how to represent their knowledge to others for specific purposes, and asking what the grounds are for believing science ideas to be valid.

From an equity standpoint, it means that young learners need regular opportunities to "try out" the conceptual, social, epistemic, and material work of science. At the same time, teachers need to make explicit the cultural and historical grounding of science. Teachers in this process would have to navigate tensions between canonical ways of engaging in these activities and honoring culturally specific ways of representing knowledge in its various forms, arguing about ideas, and determining "what counts" as an explanation. The implications for teachers' work are far reaching, from how science talk is scaffolded and legitimized to the ways in which students are supported in developing identities as users, producers, and critics of science. For example, because the social context of the representation, discussion, and critique of ideas plays a prominent role in this vision of science, different forms and uses of science talk should be an important part of science class. Likewise, the varied ways of theorizing phenomena, constructing evidence, and framing relationships that students bring to the science classroom should be viewed as intellectually generative, and assets in their ever-growing repertoires of sense-making strategies.

What Young Learners Are Capable Of

Two developments that have informed "learning about learning." One of the most illuminating bodies of research to develop over the past two decades focuses on the capacities of very young learners to engage in scientific reasoning and practices. These studies show that under carefully constructed conditions of support, elementary school students can think in ways and participate in activities that previously were considered beyond their developmental capabilities. Children as young as 6 or 7 can use abstractions to build complex forms of conceptual understanding; pose scientifically fruitful questions; design controlled studies and the means of collecting relevant data; construct and critique representations of both data and phenomena; develop evidence-based explanations; engage in protoforms of scientific argumentation; and reflect on their own progress in learning (metacognition in its various forms).

The insights from this work were made possible by two developments, one conceptual and one methodological. The first was a reframing of what it means to "learn science." Beginning in the 1980s, many in the research community began to conceptualize science learning not as the acquisition of bits of information or the mastery of laboratory skills, but as active theorizing about the natural world, as solving problems, and (in the process of theorizing and solving problems) as participating more fully in the knowledge-building practices of science. Prior to this, much was assumed about the learning trajectories of students, for example, that students learned best by starting with simple, concrete ideas and only later, if at all, working with abstract or otherwise complex concepts (see Sawyer, 2008). Such learning pathways were assumed to be normative. The language around conceptual learning featured deviations from it, such as preconceptions or alternative conceptions, which were targets of remediation. The school science view of the discipline itself was, by today's standards, uncomplicated and formulaic. There was little suggestion that the practices of science were inherently social or that they varied depending upon the particular field of study, nor was much attention paid to how knowledge of different kinds (theories, laws, hypotheses, concepts, principles, etc.) were used or reshaped in practice. From the school science perspective, conceptual learning and inquiry were (and often still are) treated as separate endeavors. For this and other reasons, science teaching itself was viewed as relatively unproblematic. The publications of Susan Carey and Carol Smith were notable in illuminating relationships between the ways science was taught in classrooms and the relatively naïve views that students typically developed about how knowledge is constructed in the discipline (Carey, Evans, Honda, Jay, & Unger, 1989; Carey & Smith, 1993; C. Smith et al., 2000).

Over the past few decades, conceptions of how students learn have been expanded by sociocultural theories of human experience that describe knowledge building as situated in social, material, institutional, and historical contexts. From this vantage point, learning is viewed as a culturally dynamic process. Students' and teachers' experiences, ideas, perspectives, histories, and values interact as they explore scientific ideas (Nasir, Rosebery, Warren, & Lee, 2006). Everyone—students, teachers, scientists, and everyone else—develops a range of sense-making repertoires to understand the world. As culturally grounded practices, these repertoires are as diverse as human society. Learning, then, not only is shaped through people's routine participation in varied communities of practice, but also is defined by an increasing ability to take up central roles in activity valued by the community (Cole, 1996; National Research Council [NRC], 2009; Rogoff, 2003).

Within science education, we see a growing emphasis on organizing teaching and learning to foster productive participation in the practices of scientific communities—such as argumentation, explanation, and modeling—and to incorporate the diverse ways individuals take up these practices initially. Meanwhile, research in urban settings with students from nondominant communities has expanded efforts to understand how students' experiences, funds of knowledge, and culturally mediated sense-making practices can be mobilized instructionally to support learning (Nasir et al., 2006; Rosebery et al., 2010; Varelas & Pappas, 2006). But research into instructional practices is only beginning to describe how teachers notice and respond to students' sense making. This marks a limit to our abilities to describe ambitious teaching.

The second development that laid the groundwork for understanding the potential of young learners was the use of new methods for studying learning. One of the most generative of these was design studies. Design studies entail coordinated attempts to engineer particular conditions for learning and to systematically study that learning as it unfolds (Cobb, Zhao, & Dean, 2009). Learning conditions are designed to allow certain kinds of interactions among learners, ideas, artifacts, and teachers to be observed. The methods of data collection vary but are always sensitive to the hypothesized processes involved in understanding subject matter, the influence of context, and how learners respond to changes in instruction and support. As instruction occurs, researchers attend to talk and other interactions, use of materials, and learner-developed artifacts, as well as to more traditional forms of assessment in order to document learning and inform revisions to the design (A. L. Brown, 1992; Cobb, Zhao, & Dean; Collins, 1999).

Design studies often map the social as well as the individual cognitive development of knowledge in various settings. So in addition to paying attention to phenomena such as novice versus expert performances, the use of prior knowledge to inform new ideas, or building from concrete to abstract knowledge, these researchers also attend to theoretical activity that applies to groups of individuals working together. This includes phenomena such as legitimate peripheral participation within communities, apprenticeship, guided participation, use of social discourses, identity work, scaffolding, creating and critiquing public representations, and collective reasoning.

Resetting the boundaries of children's science reasoning and activity. As we argued earlier, young learners are capable of far more sophisticated forms of reasoning and science activity than previously thought. But the conditions necessary to support such learning are fundamentally different from those found in most science classrooms today. To elaborate on these assertions, we review what has been learned about children's science reasoning and conditions that support advanced learning. We focus primarily on young learners, in part because they exemplify how their actual capabilities contrast dramatically with the modest expectations of current curricula and teaching, and because these findings have implications for recalibrating the trajectories of middle school and high school instruction.

Some of the first widely recognized design studies were part of the Fostering a Community of Learners (FCL) project, directed by Ann Brown and Joseph Campione for 15 years in the 1980s and 1990s. Working in K–8 schools, they were pioneers in coupling inquiry with other activities that cultivated deep domain knowledge (A. L. Brown & Campione, 1994). In FCL classrooms, students were introduced to a set of science ideas through a story or video. Students were encouraged to ask questions—a process that was guided by the teachers to ensure that important themes identified by the project team were represented in the dialogue and were later investigated. One recurring activity structure was the "research-share-perform" cycle, which involved reading and analyzing texts of various kinds, some of which described results of scientific studies relevant to the domain under study. Students would divide into small teams and adopt a question to research, such as a question about food chains or food webs. Students were encouraged to develop specialized expertise and share that expertise with others. Metacognition was a theme of FCL, much of it in the service of increasingly complex argumentation and explanation. The goal was to turn over to students the responsibility for both the progress and the evaluation of their own learning. Students in these classroom communities excelled over successive years on tests of both literacy and science, routinely outscoring learners in control groups.

In the 1990s another group of researchers began to study the relationships between conceptual understanding and problem solving. The Cognition and Technology Group at Vanderbilt University created "macro-contexts" for learners, which involved descriptions of authentic situations or story lines that included mathematics (such as planning travel) or science (such as the mechanics of flight). As with FCL, students were encouraged to identify problems to be solved, seek resources to work on these problems, and monitor their own progress toward important goals. The anchoring environments, supported via videodisc technology, were designed for students to develop the general skills and attitudes necessary for problem solving and also the knowledge of specific conceptual content that would allow them to reason about the domain (Cognition and Technology Group at Vanderbilt, 1993). Over several years, the research program built a case for two conjectures that linked studies of expertise outside school settings with conditions that could be applied in the design of classroom instruction (see Bruer, 1993, for more on applying promising learning theory of the time to formal instruction). The first conjecture concerned metacognition. The premise of the conjecture was that individuals who actively monitored their current levels of understanding were more likely to take steps to improve learning, including moves to identify relevant tools, knowledge, and other resources to assist progress. The second conjecture concerned the interdependence of reasoning skills and conceptual understanding—that learners need rich forms of content knowledge (concepts, theories, and facts) as a foundation as they develop their capacity to think scientifically, and that this reasoning in turn further develops meaningful connections among concepts.

More recently, Palincsar and Magnusson (2001) developed an approach that blends the kinds of textual instruction that characterized FCL with an emphasis on getting students to understand how knowledge claims are developed and tested in science. In reporting on their work teaching the nature of light to kindergarten and fourth-grade students, they emphasize eliciting and building upon students' prior knowledge and making explicit how the standards of talk required by science are different from the standards of everyday discourse (Magnusson & Palincsar, 2005). For example, students are taught that patterns in observations are stated as knowledge claims, claims are judged on the quality of evidence that supports or disconfirms them, hypotheses take on the status of claims only after they have been tested, and claims are not considered scientific knowledge until the community has weighed evidence from a range of observations and tested alternative explanations. In the spirit of FCL, all activities and resources are linked to an overarching theme and set of student-generated questions (in this case, questions about the interaction of light with materials). These researchers found that elementary school students could understand and participate in suggesting experiments, express cogent claims, and collectively adjudicate the strength of evidence for assertions about the behavior of light. As with the two research programs previously described in this section, the authors found that repeated, iterative cycles of inquiry were key for learners to develop a deep conceptual understanding and a sense of how to participate in conversations about evidence and claims.

Another research program, this one by Kathleen Metz and extending for more than a decade, focused on students' ability to design and execute independent forms of inquiry. In her work, children are immersed in one discipline, often for a year or longer (e.g.., ornithology, animal behavior, or evolution), developing domain-specific knowledge that Metz has demonstrated as crucial to supporting the development of inquiry skills and scientific reasoning (Metz, 2004, 2011). In the early stages of children's involvement, investigations are carefully scaffolded[1] (definitions of scaffolding vary; see footnote) while the core methodological and epistemic features of inquiry are maintained. As children learn to participate in these ways of posing and answering questions, they take up tools, representations, and forms of data analysis that are particular to that domain. Later, children are given increasing responsibility for the design and evaluation of scientific investigations.

In Metz's work, second, fourth, and fifth graders (2000) have woven together the epistemic and social dimensions of practice. For example, in studying animal behavior, students recognized that failing to agree on a hypothesis was not a problem if they could justify their beliefs using logic or data. These students eventually developed heuristics for evaluating potential questions; each team planned and carried out its own investigations. In one study, all student teams in a second-grade classroom and in a mixed fourth- and fifth-grade classroom were able to formulate both research questions and methods for investigating their questions. Some teams even proposed methods for controlling extraneous variables.

In yet another example of longitudinal research on the coordination of scientific thinking and practice, C. Smith et al. (2000) conducted multiple studies of students in an elementary school, using the framework of conceptual change to support explanations for science phenomena and debate competing explanations produced by class members. Researchers were particularly interested in students' evolving criteria for what counted as a "good explanation." Like Metz, Brown, and the Cognition and Technology Group at Vanderbilt, lead teacher Hennessey placed a great deal of importance on students' developing metacognition, attending to the status of their own theories based on their own current reasoning and evidence. And as with programs of research previously described in this section, Hennessey

[1]The metaphor of *scaffolding* is widely used in education, but has been described in a number of different ways. *Scaffolding* refers to temporary forms of assistance for learners who are faced with instructional tasks that are just beyond their current capabilities (Wood, Bruner, & Ross, 1976). Used by mentors or well-informed others in these situations, basic scaffolding moves can include structuring the task itself (how it is represented to the learner), providing specialized tools, coaching learners as they work on the tasks, modeling or "thinking out loud" about how to approach different aspects of the task, focusing learners on particular aspects of the task, and providing timely comments. Some scaffolding interactions may also problematize students' work in order to force them to engage with key disciplinary frameworks and strategies (Reiser, 2004). Such scaffolds act by "rocking the boat" for learners who are simply following procedures, thus redirecting their attention to goals, such as evaluating scientific claims, articulating explanations, or reflecting on progress. In scaffolding, the task itself is not simplified; rather the roles learners are asked to play in completing the task are modified, depending upon their current levels of understanding and skill. The process is not unlike a cognitive apprenticeship (Collins, 1991) in which the goal is for learners to take more responsibility over time as they become more independent problem solvers. The nature of the tasks and the extent of scaffolding for learners necessarily changes, then, as learners become more competent.

began units by having students explore a phenomenon chosen to provoke surprise and puzzlement. Students then engaged in lab or field studies, some designed by the teacher and some of their own design, recording questions that came up in the context of these explorations. Students represented their ideas in drawings, diagrams, maps, and so on, and compared the ideas embodied in these inscriptions with those being developed by their peers. These representations changed over time as students examined a wider range of evidence and developed more justifiable theories. Hennessey's students developed sophisticated understandings of the goals of science, the types of questions scientists ask, the nature and purpose of experiments, and what causes scientists to change their ideas (Carey et al., 1989). C. Smith et al. (2000) reported that 6th graders from Hennessey's classroom demonstrated epistemological understandings of science that were similar to or exceeded those of typical 11th graders.

Lehrer and Schauble (2003, 2005, 2012) have conducted a program of research with children ranging from first to fifth grades, focusing on the themes of growth and change in living systems. Their primary interest is in students' capacity to engage in modeling, which they frame as putting representations to work, mobilizing them to support and revise empirically grounded arguments about the nature of physical reality. Participating teachers in their projects build on children's interest in representing the world in a variety of ways—via language, drawings, physical models, maps, and patterns. They also engage learners in the scientific practices of quantifying or visualizing phenomena geometrically. Students learn to use concepts of measurement and ideas about data and uncertainty to understand both mathematical change and the underlying physical phenomenon that is being represented. Instruction is oriented around important biological themes, such as growth and diversity, behavior, structure, and function. Students in early elementary grades, for example, learned to use their own representations of plant growth to ask questions about how much faster one specimen grew than another, turning their attention from comparing final heights to noting successive differences in change itself from the day-to-day measurements.

As a result, Lehrer and Schauble (2000, 2003, 2005) have identified qualitative shifts throughout elementary school in children's understanding of modeling. In the early grades, students learn best from work with models that physically or pictorially depict objects and the relations between their parts. In later grades, they use these representations with models that are progressively more symbolic and mathematically powerful. All categories of these models, as representational resources, both accompanied and catalyzed conceptual change. The conversations about new science ideas and the varied forms of inscription appeared to support each other, and the "back and forth" reasoning opened up new lines of inquiry. As with other programs of research cited in this section, substantial learning effects have been documented, in this case from grades one to five (Lehrer & Schauble, 2005), with students in these early grades outperforming much older students on nationally benchmarked assessment items.

Expanding our views of students' sense making in science (expanding how we think about what children are capable of). As teachers engage students in the kinds of learning tasks described in the studies discussed in the preceding section, diverse histories, experiences, ways of knowing, and discourses interact. Warren and Rosebery argue that we should think of science teaching and learning as an "intercultural process" that takes place at the "powered boundaries of race, culture, language, and subject matter" (2011, p. 1; see also Rosebery et al., 2010; Rosebery & Warren, 2008). Classrooms are places of "heteroglossia," where "varied ways of conceptualizing, representing, evaluating, and engaging the world in language" are juxtaposed as teachers and students come together around new science ideas (Rosebery & Warren, 2008, p. 325).

The act of teaching involves attending to and responding to students' diverse everyday discourses, cultural practices, and experiences, which they bring to sense making in science. But not all forms of sense making are legitimized in the classroom. Expectations for productive or meaningful science teaching and learning interactions are established by the dominant culture. Certain ways of knowing, seeing, speaking, writing, acting, and valuing are privileged over others, in society as in school (Heath, 1989; Ladson-Billings, 2003). Such privileging can make it difficult for students from historically marginalized groups to participate fully in school science—to demonstrate what they are capable of—especially if their varying discourses or resources go unrecognized or are labeled as inferior.

Viewing science teaching and learning as intercultural processes is a productive but complex stance. It foregrounds who learners are, how they come to know science in deeply socially situated ways, and what they are capable of doing in science class. These points are pivotal in framing discussions of what students are capable of. Historically, students from nondominant backgrounds—nonwhite, lower-income, and English-language learner students—have been positioned as disinterested in science and on the wrong side of the achievement gap. And yet a growing body of literature reveals how instructional practice and legitimized discourses in science classrooms affect how students are perceived as capable learners, and the relevance and value of the knowledge they bring to the learning process (e.g., Calabrese Barton & Tan, 2009; Carlone, Haun-Frank, & Webb, 2011; Gonzalez & Moll, 2002; Moje et al., 2004). Instructional expertise requires that teachers learn to recognize students' ideas, experiences, and the cultural resources they bring to learning, identify how students' resources potentially connect with the knowledge, and develop pedagogical strategies based on that understanding.

Several studies draw attention to the role of classroom teachers in eliciting and validating students' everyday discourses, cultural practices, and experiences as intellectually generative. Some of these studies focus on ways of knowing or sense making, while others focus more explicitly on the knowledge and practice toolkits that students bring to learning science. Although these approaches overlap, as we highlight in the text that follows, they also offer important tools for framing ambitious teaching.

In a study investigating third and fourth graders' learning about heat transfer (Rosebery et al., 2010), the authors illustrate how the youth, all from nondominant backgrounds, used cultural knowledge and experiences in ways deeply relevant to both the science of thermodynamics and their experiences at home. For example, the authors demonstrated how African American students often imagine themselves as part of science, and of the scientific phenomenon they are trying to understand, even when they feel marginalized by norms and practices of school science. Here, sense making is tied to both "what" students are learning (the central ideas and practices) and the "ways of understanding" the world that children bring to science. The authors make an important point about how the children in the classroom used language in ways that promoted "transformative contact between different points of view and its relation to expanding understanding" (p. 338). They show how the terms the children used, such as "hotness" and "huddled our heat," were novel, or "linguistic innovations," that best reflected their emerging understanding. These were not science terms per se, but rather terms that bridged their everyday understandings with their attempts to make sense of the second law of thermodynamics. These terms gave substance to their experiences, and helped them to "see" the phenomenon they were interested in. Had the teacher not taken these terms seriously and as important scientific ideas, this pathway to understanding could have been lost. Here, the teacher designed instructional encounters with the aim of "fostering contact among varied languages and points of view in order to generate learning of disciplinary ways of seeing the world" (p. 351).

Next, we highlight a study that looks at the use of drama by early elementary school students in their study of two integrated science-literacy units about matter and forests (Varelas et al., 2010). The authors wonder about "the possibilities and challenges that arise as children and teachers engage in scientific knowing through such experiences" (p. 306). In particular, the researchers are interested in the "togetherness of dramatizing" (p. 306), or how the dramatizations foster productive scientific discourse. Reminding the reader that all learning and action is mediated, they articulate how new understandings of the particulate nature of matter among young people emerged through collaboration and interaction. They show how drama—using the whole body as a tool to imagine science—supported multimodal sense making, allowing for greater opportunities to negotiate ambiguity around concepts and communicating meaning. These findings seem particularly salient given that the children were exploring ideas, according to the national science standards, several grade levels above expectation. Additionally, the dramatic enactments of the scientific ideas under investigation operated on "multiple mediated levels": as "material objects that moved through space, as social objects that negotiated classroom relationships and rules, and as metaphorical objects that stood in for water molecules in the various states of matter or for entities in a food web" (p. 320).

Some studies, which explicitly focus on what students are capable of, examine the "funds of knowledge" that students bring to the classroom. Funds of knowledge are the culturally based understandings and practices that develop in family and neighborhood contexts, and that can be used to support learning and participation within a new community of practice, such as the classroom (González & Moll, 2002). Moje et al. (2004) analyzed the "intersections and disjunctures between everyday (home, community, peer group) and school funds of knowledge and discourse that frame the school-based, content area literacy practices" of middle school youth (p. 39). The study was conducted over five years, among 30 Latino and Latina youth in Detroit, Michigan. What the study reveals is that there were clear patterns in both the connections that students made between their everyday funds of knowledge and science, and the ways in which they leveraged their funds of knowledge to learn science. The authors highlight four core areas of knowledge: (1) family, (2) community, (3) peer groups, and (4) popular culture. As the authors illustrate these funds they link them to their attendant discourses and point out the ways in which the funds and discourses are connected or disconnected from the science classroom. For example, in discussing funds associated with work in the home, Moje et al. describe how youth learned to observe activities in the home, such as different cooking procedures, and from these observations develop important insights into scientific phenomena:

> During a lesson on complete and incomplete combustion, a seventh-grade girl used the frying of tortillas to explain her argument that smoke was not white, as the teacher had claimed, but black.…Had the teacher heard this whispered comment, he could have used Tana's knowledge of the "black stuff" produced in burning to clarify his point and to extend the discussion on combustion. (p. 53)

In addition to providing sources of knowledge for scientific phenomena, Moje et al. also reveal how funds of knowledge position multiple discourses as central to knowing and doing science. Citing the example of youth experiences with familial jobs in "dry-cleaning establishments, construction sites, and auto plants, all industries with direct connections to community air and water quality issues," the authors make the argument that family work in these areas fosters an awareness of the "economic and social consequences of scientific activity," making talk about science more complex (p. 52).

In another study, Sharma (2008) describes how students in an Indian village called upon culturally based discourses and knowledge about electricity gained from familial experiences with household electrical circuits to negotiate new positions for themselves in the school science discourse. This insight is particularly important because the author shows how students positioned themselves related to their opportunities to demonstrate what they knew, and this opened and closed opportunities for them to learn. The author argues that teachers need to learn to draw upon students' discourses, rather than marginalizing them, and merge them with the intended scientific discourse—a view that is also articulated in sociocognitive literatures and linked with productive reasoning by learners (see, e.g., Mortimer & Scott, 2003).

The communities traditionally associated with generating funds of knowledge are families and household clusters. But some studies in science education also point out that the knowledge, practices, and discourses derived from student-based communities, activities with peers, and popular culture can also be considered critical sources of experience for engaging learners in sophisticated scientific thinking (Calabrese Barton & Tan, 2009; Moje et al., 2004). Calabrese Barton and Tan show how one teacher's approach to incorporating students' home and community funds of knowledge around food practices—in order to teach about homeostatic equilibrium and the human body—led students to increase their learning outcomes in this content domain, and to exhibit strong science identities. For example, the teacher worked with students to cocreate a series of lessons that incorporated their concerns and ideas. The students created a $2 "bodega challenge," which charged peers, in groups, with purchasing the healthiest snack for $2 at the corner store, and with warranting their choices based on their knowledge of healthy eating. The use of student knowledge from family, community, peer culture, and popular culture opened up new discourse spaces and positioned students as experts. Students who normally didn't participate became deeply engaged in scientific talk and thinking. This study and the previous studies suggest that what students are capable of in science is related to how they can leverage everyday discourses, knowledge, and practices in taking up scientific problems and ideas.

Because children come to classrooms with knowledge and strategies for making sense of the world, it is essential that teachers learn to recognize and respond both to what children know and to what they need to learn. In the past decade, the research community has begun to develop tools and approaches to help teachers elicit and acknowledge students' varied cultural resources for learning (McLaughlin & Calabrese Barton, 2013).

Take, for instance, Zimmerman's (2012) ethnography of the experiences of one youth (Penelope) in caring for animals at home and interacting with peers at school. In this study, Penelope's deep engagement with animals led her to develop a rich toolkit of science practices, such as observational inquiry, using text and media to understand animal behavior, experimenting with feeding protocols, and designing and refining indoor habitats and routines that kept her animals happy and safe. Penelope leveraged these practices and became seen as an animal expert in informal settings. For example, friends would email her to ask for animal advice, and members of her after-school club would also consult her for animal advice. These settings mattered to her, but Penelope did *not* leverage these practices (and her related identity as a science expert) in science class, because it was a setting that did not matter to her. Instead, she engaged in discourse and activities that supported her being recognized as *disinterested* in science. This study shows that "recognition work is a complex negotiation between aspects of one's self and of science" (p. 497), which can shape how students are recognized in school. This study raises methodological concerns. Had the author not followed Penelope to these out-of-science-classroom spaces, the author might not have known what Penelope was capable of.

Using Similarities Across Research Programs to Inform a Vision of Ambitious Teaching

The architecture of opportunity for students. The programs of research just described share a set of instructional design features that appear to enable progress toward unusually sophisticated forms of thinking and investigation. Each, for example, focuses on scientific ideas that are central to the discipline and afford many avenues along which students can develop competence in conceptual understanding and inquiry. More important, however, is "what changes over time" in each of these studies: *(1) student thinking, (2) the ways students learn to recognize the specific qualities of their own ideas, and (3) the ways students learn to interact with others as they engage in science as practice.* Student ideas become the explicit objects of interrogation and revision by students themselves. Learners identify puzzles about or gaps in their understanding, and seek various resources or information needed to move forward, the way they engage in authentic problem solving in out-of-school settings.

In the work of A. Brown and Campione (1994), students were asked to evaluate their own understandings of a topic before they attempted to teach it to others. In Metz's (2004, 2011) work, young learners had to regulate their progress toward the objective of designing and carrying out their own studies. For Magnusson and Palincsar (2005), as well as Smith, Maclin, Houghton, and Hennessey (2000), children were constantly asked to reflect on the basis of the claims they were making about data and phenomena. Lehrer and Schauble (2005) asked their students to choose visual representations of mathematical ideas and put these representations to work in the service of arguments about qualities of natural systems. Agency, then, in some form characterizes this work, but it is always accompanied by strategic forms of scaffolding for conceptual learning, investigations, explanations, and proto-forms of argument.

Each of these programs of research conceptualizes learning through a different lens—theory building, progressive discourse about science ideas, constructing and testing models, or conceptual change. But they all feature the evolution of students' ideas in response to evidence, the opportunity for public conversation, new questions, new ideas, and ultimately intellectual engagement. What seems obvious from the preceding examples is that science as practice must, by definition, include opportunities for learners to participate in these practices. Learning through practice is powerful because the *conceptual, social, epistemic, and material dimensions of scientific work, taken together, catalyze changes in reasoning and activity*.

Looking across these research programs and other studies that demonstrate how students of all backgrounds can be capable of challenging work, a list of characteristics emerges that more clearly describes ambitious teaching:

Teachers' framing of students' relationship with the intellectual work:

- High expectations for academic work by students were implicitly supported in a range of ways.
- Students were engaged in authentic scientific practices, and in ways that made them legitimate peripheral participants in the larger investigative enterprise.
- Students' sense-making repertoires were treated as intellectually generative.
- Students were given increasing responsibility for assessing their own understanding, for selecting resources to move their thinking forward, and for evaluating progress toward important goals.

Conceptual anchors for the collective work:

- Complex and richly contextualized phenomena, which involved important underlying science ideas, anchored students' intellectual engagement over an extended period.
- Explanations of how and why phenomena occur were an instructional priority.
- Coherence was built in across different learning activities and among the bigger science ideas featured in the unit of instruction.
- Science skills were not taught separate from the cultivation of subject matter understanding; rather, the conceptual, social, epistemic, and material dimensions of the work were always interwoven.

How teachers mediated student reasoning and activity:

- Instructors had clear learning and participation goals; individual activities were designed to work toward these.
- There was a progression of experiences, which were frequently adapted to learners' current needs.
- Instruction regularly incorporated students' ideas and everyday experiences as resources for the furthering of everyone's understanding.
- Scaffolding tools and moves were used by teachers and students to support specialized forms of reasoning, talk, and other interactions.
- Discourse was used far more broadly than in typical classrooms, for a wider variety of purposes, and by students as well as teachers to do the following: prompt sense making and reasoning, make students' thinking visible, reinforce the norms of science talk, "seed" conversations with new ideas, make confusion public, and position young learners as competent knowers of science.

Accounts of research programs that report multiple forms of successful learning may make it seem reasonable to replicate such instruction in schools. But reform ideas cannot be implemented quickly. The instruction in these studies was often heavily resourced in terms of time available for instructors to plan and to adapt curriculum to learners' needs. Instructors were often experienced or master teachers. There was also time for students to explore science ideas in much greater depth than is usual in most school settings—in some cases, instruction on a particular topic or theme lasted months. Often the instruction was designed with help from experts (e.g., scientists, engineers, or university education faculty). The relevant questions, then, are, What features of these instructional systems are necessary for supporting learning by both students and teachers? How can such conditions be made commonplace in our schools**?**

Implications for rigor and equity. Children are capable of more sophisticated reasoning and science-related activity than our current educational system supports. Popular images of learning, which have not changed substantially in the past few decades, are constraining the curriculum and teaching practices of educators throughout the K–12 system. Rigorous and reasonable expectations, calibrated by findings across recent studies, suggest that students should be able to make decisions about how science practices can be used to test and revise ideas, use a variety of ways to represent their thinking to others, reflect on their own understanding, evaluate evidence and explanations in flexible ways according to the subject matter under study, and make judgments about the resources they need to accomplish learning goals.

The skills required of teachers to support this work by students are varied and substantial. Experienced teachers, who may have deeper content knowledge, an understanding of how curriculum unfolds for different groups of students, and skills for managing student interactions, seem best positioned to take up the ambitious forms of instruction described.

Unfortunately, underserved students, who most need support for engaging in this type of science, tend to have less experienced teachers and fewer classroom resources at their disposal (Alliance for Excellent Education, 2008; Darling-Hammond & Post, 2000). In our focus on teaching practice, we need to remind ourselves that the kinds of learning environments our students have access to are powerfully shaped by an entire system of schooling—a system that often makes the translation of credible research to classroom practice frustratingly difficult.

Why Identity and Positioning Matter in Framing Ambitious Teaching

Prevailing models of schooling and of science teaching—many labeling themselves reform based—continue to be organized around a transmission and acquisition theory of learning.[2] Such a perspective seeks to move learners along a one-dimensional continuum from “not knowing” a particular kind of content on one end to “knowing” on the other. Children, however, are not one-dimensional. They bring their whole beings to the classroom, and recent scholarship has shown how learners’ culturally situated experiences, ways of communicating, modes of sense making, and perceptions of self as knowers in school settings influence how they engage with science. This, then, has implications for ambitious teaching, in terms of educators recognizing a wider array of resources and identities that students bring to the classroom, and for being responsive in terms of using these resources and identities to further instructional goals.

There is ample evidence that students’ identity work mediates science learning and engagement, and occurs in dialectic with the sociohistorical structures of the learning community. Identity is framed through sociocultural and situated theories and generally refers to who one is or wants to be, as well as to how one is recognized by others in social context (Gee, 2000-2001; Holland & Lave, 2009). Identities are constructed interactively through practice, which requires knowledge, skills, and ways of thinking that characterize, in part, the discipline in which one is engaging. There are also broader disciplinary narratives about what it means to be scientific, normative education narratives about what it means to be a good student, and cultural narratives about what it means to be a girl, a boy, an African American, an English Language Learner, and so on. The process of becoming within the science classroom reflects a student’s developing knowledge and practice and how he or she is recognized by others for developing expertise (e.g., Calabrese Barton, Kang, Tan, O’Neill, & Brecklin, 2012; Carlone et al., 2011). The majority of identity-related studies have focused on the relationship between the process of becoming (the identity work) and the social context (science class, science club, peer group, etc.). There are at least three strands of research on the kinds of identity work that happen in the science classroom: (1) student engagement and the kind of person who does science; (2) the mediating role of the sociohistorical structures of the classroom in identity work; and(3) pedagogical practices in support of productive identity work. In the text that follows, we summarize several of the major findings in these areas, highlighting illustrative examples from the literature.

Student Engagement and the Kind of Person Who Does Science

Studies suggest that students’ engagement or participation in school science is influenced by *whether and how they view themselves as the kind of person* who does science (or school science). This finding focuses on the identities that the individual learner brings to school science and how the learner views and positions himself or herself with respect to the norms, routines, and practices of school science. Brickhouse and colleagues were early researchers in examining how identities mediate learning (c.f., Brickhouse et al., 2000; Brickhouse, 2001; Brickhouse & Potter, 2001). They drew upon Lave’s theories of situated

[2]Parts of this section are based on the manuscript “Identity Research in Science Education: Implications for Integrated Experiences and Best Practices” a white paper commissioned by the National Academy of Sciences Board on Science Education (Calabrese Barton, 2012).

and participatory learning to argue that learning science and identity development in science are inseparable: "As students transform their identities, the requisite knowledge and skills for being a part of the new communities are learned." Brickhouse et al. documented the experiences of a small group of African American girls throughout the seventh grade. All the girls strongly identified with and felt competent in science in out-of-school settings. But despite this interest and competence, the girls' engagement with school science varied markedly. Some were interested in school science but others were not. The authors posited that differences in participation were related to how teachers were able to support the girls' out-of-school science identities (i.e., "I am good at building things"), in conjunction with expectations for learning in the classroom and what it meant to be a "good student." Expectations for being a good student were overtly tied to the social roles and gendered norms of compliance that operated in individual teachers' classrooms. Classroom instruction did not allow for "a wide variety of ways to engage in science" (p. 455). Later studies (Brickhouse & Potter, 2001) showed that girls can accrue particular advantages if their out-of-school science identities align with "ideal" identities that teachers support in classrooms. For example, contrasting the cases of two African American girls, the authors demonstrate how one of the students was able to leverage her computing expert identity toward success in a vocational track, while the other shifted from being a star science student to a failing student when, upon moving to a new school and finding herself the only African American girl in her class, she was unable to socially connect in her classroom and be recognized by others (including her teacher) for the expertise that she brought. Her teacher described her as a "sweet girl" who was "good with language" and strongly supported moving her from the honors track to the vocational track. The study concludes that if girls are to be able to leverage their identities toward productive learning in new or different contexts, then they must have meaningful social interactions around the resources salient to that identity development. The studies also reveal the powerful role that teachers have in disrupting low expectations and associated identity work within the broader social context of the classroom.

The Mediating Role of the Sociohistorical Structures of the Classroom in Identity Work

A second major claim related to identity focuses on how the sociohistorical norms, routines, and practices of school science make possible particular forms of engagement and particular kinds of learning because of how they set up what it means to have a good school science identity. In a study of high school girls enrolled in an Active Physics class, Carlone (2004) found that the possible identities supported by an innovative reform-based curriculum were different from the possible identities supported by the norms and routines of schooling. Many of the girls in her study, who were from white and upper class backgrounds, were primarily concerned with school performance. They attended closely to classroom activities in order to perform (and ultimately privilege) the "good student" identity (in line with the norms and routines of schooling) over the "scientist" identity (in line with the curriculum). Thus, despite the teacher's efforts to enact innovative curriculum intended to be more gender-fair, the girls' focus on grades and achievement, supported by the broader structures of schooling, prevented their meaningful engagement with science *and* blocked their opportunities to develop science identities.

Culturally produced meanings of science and scientists that are supported by classroom instruction also are significant in how elementary school students author possible identities in science. Carlone et al. (2011) examined what it meant to "be scientific" in two fourth-grade classes taught by teachers similarly committed to reform-based science practices in the service of equity. Although students in the two classrooms achieved at similar levels, and expressed positive attitudes toward science learning, distinct differences emerged in what it meant to be recognized as a smart science student. These differences were grounded in two critical aspects of the social system: (1) how and why teachers asked their students to share ideas and tools in whole-class settings, and (2) how the teacher framed the purposes and outcomes of investigations. One of the teachers, Mrs. W., supported a wide array of science practices, fostering a classroom culture where scientific expertise carried a range of meanings, and thus greater opportunities for active engagement. The other teacher, Mrs. S., maintained narrowly constrained views of being scientific, thereby limiting opportunities for students to engage actively with science.

As part of the learning environment, educators must consider the role of sanctioned discourses. A set of studies examines how allowable classroom discourse practices limit and mold the identities that students construct. In a narrative analysis of classroom conversation groups held with high school students about their project-based investigation of the socioscientific issue of health and the human body, Ideland and Malmberg (2012) show that students moved between many discourses, including a general school discourse, a school science discourse, and a cultural norms discourse (in this case, the cultural norms of body health, the topic under investigation). Students moved through these discourses differently based on their own experiences with gender and race. Teachers also played important roles in enforcing these subject positions.

For example, the authors illustrate how one teacher did not subject boys to the same expectations for being good science students as girls—boys were allowed to be more critical of scientific text and ideas than girls were. And although the boys felt free to engage science in less constrained ways, their own histories as "easygoing lads" in the classroom constrained their ability to actively appropriate science terminology. Like Carlone et al.'s (2011) finding in high school physics classrooms, this study shows that students hold multiple identities simultaneously, and these identities might compete with each other, such as the "being a girl" and "being a scientist." How students were able to take up these different identities and find ways to merge them productively in class related to the allowable classroom discourses and how these positioned the students.

B. Brown (2004, 2006) has also addressed the question regarding allowable classroom discourses and their relationship to students' identity work. His 2004 publication examined how students differentially appropriate classroom discourses, leading to different pathways of identity development and opportunities for meaningful learning. The results of his study indicate that discursive moves supported by teachers and enacted by students positioned students along a continuum from "oppositional" to "proficient," with oppositional students avoiding the use of scientific discourse and proficient students demonstrating fluency in scientific discourse. B. Brown (2004) argues that one reason some students identified with the oppositional end of the spectrum was because a cultural conflict resulted from appropriating discourses and their attendant ways of being when they differed from their own practices. In other words, the resulting "discursive identities" are decisions on the part of students to be recognized vis-à-vis science in particular ways.

Here, and in other, related publications, B. Brown concerns himself with *cultural conflict* as integral to the ways in which ethnic and language minority students undertake identity work through discourse in science class. He argues that an important factor limiting minority students' learning is the conflict between their home discourse and modes of nonvernacular classroom discourse (Gee, 1999). That is, science classrooms have unique discourse environments, which can place minority students in cultural conflict. Because discourses are deeply tied to identity work—"discourse can serve the purpose of indicating who an individual wants to be perceived as" (B. Brown, 2004, p. 813)—then "minority students' identity has the potential to stand at odds with the culture of schooling" (B. Brown, 2006, p. 98). Neither of Brown's studies describes the curricular or pedagogical approach in detail, but the studies make clear that additional work on how teachers' instructional practices influence cultural conflict is important.

Pedagogical Practices in Support of Productive Identity Work

The identities that learners develop are also a response to the design of the learning environment. Shifts in school science identity require a complex combination of pedagogical approaches, curricular orientations, and broader support of classroom and school culture. Some studies (Calabrese Barton & Tan, 2009; Calabrese Barton et al., 2012; Calabrese Barton, Tan, & Rivet, 2008; Tan & Calabrese Barton, 2008a, b) directly link teacher pedagogy, including the use of student stories in the classroom and student-led projects that foster hybrid practices, with the ongoing use of multiple social configurations and interactions that support different forms of engagement.

One example is the case of Melanie (Tan & Calabrese Barton, 2008a). In sixth grade, Melanie was transformed from a marginalized and failing student, whose peers rejected and regularly mocked her, to a science expert whom others turned to for help. The study traces how interaction patterns in the different structures of classroom work (i.e., whole-class work, small-group work, and individual tasks) offered Melanie unique opportunities for identity formation that, with recognition by her peers and teachers, she built upon across such spaces, in ways both productive and unproductive. The authors point to a series of critical events that led to instances of recognition of her work, which through dialogic interplay supported Melanie in establishing her place in science class. Here she was slowly exposed to an increasing amount of risk while she participated in new ways. Simple acts, such as pretending to be a mother giraffe to get herself through her science presentation on habitats, or enlisting her friends to act as chimpanzees so that she could give her report on Jane Goodall with them at her side—and then having these *non*-normative actions held up by her teacher as exemplars—helped create a safe space for her to think of herself and have others think of her as a creative expert in science.

The findings presented in this section are all grounded in qualitative studies, most of which involve children and youth from underrepresented backgrounds. Most present narratives of learners deeply interested in, engaged with, and competent in science, all of which challenges a widely held tenet that minority youth are disengaged from science. The studies reveal that the mechanisms for *dis*engagement in school science are complex. It is only when classroom practices and expectations align with how individuals view themselves in science or that merge academic and disciplinary discourses with identities, that more meaningful participation becomes possible (e.g., merging a problem-solver identity with a task that requires one to be a problem solver). Across these studies, we see that classroom curriculum and instruction tended to favor those aspects of a science identity that were more reflective of schooling than of science itself, thereby limiting engagement of youth who held strong science identities and appeared to have rich backgrounds in science from nonschool experiences (see also NRC, 2009).

Implications for Rigor and Equity

Why include literature on identity work in a review of ambitious science teaching? How do identity studies inform ambitious teaching? Identity research helps explain the ways in which reforms succeed—and ways in which they fail, even when they take into account gender, race, and language concerns. Students come into classrooms expecting certain forms of instruction, with histories of being certain kinds of people vis-à-vis school science, and with particular repertoires of practices for being in school. Without clear pedagogical pathways and without explicit scaffolding for navigating tensions, students continue to construct classroom practices and identities in response to the normative routines, mitigating potential benefits of the reforms. More research is needed on instructional approaches for ambitious teaching that supports youth in using their culturally based knowledge and experiences toward authoring productive identities in science. Based on the research reviewed here, there are clear directions that ought to be considered.

First, ambitious teaching should provide students places to collaborate with teachers on modifying, adapting, or refining instruction. Examples in the literature show promise in promoting teacher awareness of students' cultural resources for learning and identity work. More research is required to determine how effective such approaches are, and to determine their feasibility on a larger scale.

In addition, we have empirical evidence that teaching practices can be collaboratively reauthored by teachers and students in ways that support mutually agreed upon views of the "ideal science student." Another pathway involves consideration of the heterogeneity of experience that individual learners bring to the learning environment. Some studies suggest that learning environments that recognize multiple kinds of resources and forms of expertise support student movement from outsider to insider status, that is, from a sense of self that "science is not for me" to a sense of self as science expert. This suggests that future studies need to develop analytic approaches that enable researchers to see and to account for variation in ways of knowing and being in the classroom.

Finally, for ambitious teaching to fully incorporate the kinds of equity concerns raised by identity studies, research is needed in the development of pedagogical and curricular tools that will support teachers in recognizing, interpreting, and leveraging students' culturally based knowledge, practices, and experiences. These tools should help teachers consider how their pedagogical and curricular ideals support a diversity of sense-making modes and identities. For example, when teaching practices purposely align constructions of science with pedagogical practice, expectations, and formative assessment, opportunities for productive identity work in science are possible (see Carlone et al., 2011). Learning science involves more than knowledge and practice goals: It involves a process of becoming.

The Role of Practice in Ambitious Teaching

In this section, the focus shifts from what we know of young learners to better defining the work of teaching. This is a metaconversation, that is, an experiment in how to talk about the reconceptualization of the technical core of science teaching. We begin by unpacking what it means to focus on teaching as practice and explain how different subject matter communities have begun to theorize about valued practices. We then present four sets of practices (in sections titled "Translating scholarship to practices") that research suggests are key to the work of ambitious science teaching. Before the practices are described, we explore the relevant research that informs the selection and characterization of these practices. The descriptions of the practices include principles for enactment, a prototypical sequence of activity that joins several practices together to achieve meaningful goals, and the tasks, talk, and tools that would be employed during these practices. This chapter section helps us respond to important questions, such as, How do we develop a language and a conceptual framing to talk about practice? How might highly valued teaching practices be identified, represented, and adopted? How can we test practices in ways that continually improve teaching—both at the individual practitioner level and across the science education community?

Over the past two decades, a new vision has emerged for science learning in which the teacher is positioned as a highly skilled practitioner, students from all backgrounds are treated as capable of sophisticated reasoning and activity, and the classroom is the setting for exploration and knowledge building. This vision has been expressed in various subject matter literatures as ambitious teaching. This image of professional work values the heterogeneity of students' backgrounds, ideas, and ways of communicating as resources for instruction, is adaptive to students' needs and thinking, incorporates students' cultural practices into instruction, and maintains rigorous standards of achievement for everyone (Fennema et al., 1993; Hill et al., 2005; C. Lee, 2007; Rosebery et al., 2010; Rosebery, Warren, & Conant, 1992; J. Smith, Lee, & Newmann, 2001). These outcomes require teachers to develop a different repertoire of skills and different types of knowledge (about both subject matter and students) than is the norm today.

Through a focus on teaching as practice, we explore the potential for recent research to support ambitious teaching (Grossman, 2011). We use the frame of ambitious teaching for two reasons. First, student participation and learning are mediated most directly by teacher decisions about tasks, talk, and tools used in the classroom. Increasingly well supported evidentiary warrants from research link certain pedagogical practices—or features of pedagogical practices—to increased student learning. These claims appear stronger for specific practices than for other features of the learning environment, such as type of curriculum, or for characteristics of teachers, such as years of experience or subject matter knowledge.

The second reason for using the frame of ambitious teaching is to provide a conceptual infrastructure for the continual improvement of teaching, which is seen as both an agenda for the science education community (researchers, practitioners, and district-level leaders) and a career-long activity for individual teachers. Without a focus on principled practice, pathways for the improvement of teaching (by the field) and teachers (as individuals) might be too theoretical, poorly defined, or reduced to procedure.

Like the idea of science as practice, teaching as practice refers to the essential activities that members of a field are socialized into as part of their professional training (Bourdieu, 1977; Reckwitz, 2002). Teaching practices are routine work devoted to planning, enactment, or reflection and are intended to support student learning. Strong examples include demonstrating to learners how one talks about supporting a claim with different forms of evidence, or using a student's out-of-school experiences to support the class's development of a science concept. There are other forms of teacher activity that could be defined as practices, but for various reasons students learn little from them. Examples include implementing curriculum without adapting it to the needs of students, having students memorize lists of factual information, or providing written or oral feedback to students in the form of "correct" or "incorrect." Of the interactions that teachers have with students around subject matter, some types have greater potential than others to engage a broad range of learners in productive intellectual work. But this conversation is precisely the conversation that is absent from nearly every type of policy literature.

Teaching practices, then, are sequences of human activity, with prototypical interactive characteristics that are aligned with a specific purpose, serving participation and learning. But teaching practice is rarely expressed in this way. What has made teacher practice difficult to improve, for both individual educators and for the field, has been the underspecified and undertheorized nature of practice itself. For example, school science routines such as "doing a lab" are roughly outlined as a sequence of events involving a teacher giving directions, students gathering and working with materials, and a culminating conversation or task that ends the activity. This is how common professional development is often structured, with teachers learning to use curriculum kits in the classroom. On one hand, the abstract character of such scripts is essential, insofar as they can serve as a general guide for work at different times and different places (Blau, 1955). On the other hand, relying on these descriptions to guide activity as complex and responsive as science teaching risks mechanistic and unprincipled implementation (Spillane, 2012).

We propose that representations of practice include a prototypical sequence of interactions between teachers and students, and the characteristic kinds of tasks, talk, and tools that work together to support learning (Sohmer, Michaels, O'Connor, & Resnick, 2009). Important to any description of practices would be the goal of the activities and a set of underlying principles. The principles would represent the underlying shared assumptions about teaching, learning, and science as a discipline that support and constrain the variations that would inevitably emerge as researchers and practitioners modified these practices under authentic circumstances.

From a performative perspective, a teacher's understanding the goals and principles of a practice is critical because this will facilitate the complex, highly situated judgments that need to be made during learning interactions, without specifying the judgments themselves (Spillane, 2012). These adaptive decisions will always involve, for example, tailoring the practice for different groups of students, who are engaging with specific kinds of science subject matter for various learning goals.

Criteria for Core Teaching Practices

In recent years, some teaching practices have come to be labeled core teaching practices or high-leverage teaching practices (Ball et al., 2009; Franke & Chan, 2007). For consistency, we will use "core" in this chapter. The criteria for core practices are based on the nature of teaching itself and on the exigencies of teacher learning over time (Ball et al.; Grossman, 2011; Hatch & Grossman, 2009). Core practices have the following in common:

- They support student work that is central to the discipline of the subject matter.
- They apply to different approaches in teaching the subject matter and to different topics in the subject matter.
- They can be revisited in increasingly sophisticated and integrated acts of teaching.

- They readily allow teachers to learn from their own teaching (examples of this are routines that make students' thinking visible and create a record of students' developing ideas and language across units of instruction in forms that help teachers reconcile these changes with instructional decisions they made along the way).

To these descriptions of core practices, we add two criteria regarding their use:

- Core practices for science teaching should be few in number to reflect priorities of equitable and effective teaching, and to allow significant time for teachers to develop beginning instantiations of each of these practices.
- Each of these practices should also play a recognizable role in a larger coherent system of instruction that explicitly supports student learning goals. A practice that is not situated within a larger frame of effective teaching may accomplish important aims, but cannot by itself address the broader agenda of ambitious pedagogy. (We recognize that the definition of *coherence* remains problematic, as does the identification of a preferred system of science instruction—there are many possibilities.)

To cite one example, a practice that we discuss later is "eliciting students' ideas in order to shape instruction." This is a discourse strategy that helps teachers build upon the science-related experiences and language that students bring to the classroom. When appropriately employed it also helps promote equitable learning opportunities.

A focus on such high-value practices, described in performative language, is one way to *make visible the technical core of teaching*. There are two advantages to being able to "see" these practices and name them, along with their underlying principles. First, the professional work associated with ambitious teaching itself becomes easier for novices to appropriate when it is framed as a set of practices that are explicit, explicitly principled, and adaptable to different instructional environments. With careful experimentation and feedback within the teacher community, variation on practice can advance the field of teaching. Second, the focus on a reduced set of practices allows practitioners and researchers to test whether the variants of each practice remain linked with greater student participation and learning. Without these evidentiary warrants, variants of practices can become matters of "personal style" rather than being informed by a community of professionals.

In the following sections we focus on literature corresponding to four types of instructional activities that compose ambitious teaching: (1) planning for students' engagement with important science ideas, (2) eliciting students' ideas in order to shape instruction, (3) supporting ongoing changes in student thinking, and (4) supporting students' evidence-based explanations. At the end of each section, we take the unusual step of representing candidate sets of core practices that map onto these activities, and we describe them in terms of the characteristic tasks, talk, and tools deployed. The tools we describe are simple—no more complex than pencil and paper—but they serve the purpose of laying out ideas, rearranging them, elaborating on them, puzzling about them, and assisting students with using ideas in the context of scientific practices.

The four instructional activities are treated as "containers" within which the teaching practices are enacted (see Figure 18.1). These sets of teaching practices have been identified in the literature as supporting goals identified in consensus documents such as *Taking Science to School* (NRC, 2007)—that is, understanding, using, and interpreting scientific explanations; generating and evaluating scientific evidence and explanations; understanding the nature and development of scientific knowledge; and participating productively in scientific practices and discourse. A recent Delphi study of science education experts (researchers and practitioners) also listed practices similar to those described below as some of the most important for advancing learning. These include eliciting, assessing, and using student thinking to shape instruction, guiding the construction and interpretation of models, facilitating classroom discourse, engaging students in investigations, and linking science concepts to phenomena (Kloser, 2014). But the question remains, Can valued but separate teaching practices be integrated into a larger, coherent vision for the support of student learning?

The representations we provide of planning and instructional activities—and their constituent practices—are, of necessity, simplified and problematic. Here is why. First, each practice requires specialized but tacit forms of teacher knowledge (of content, students, social interaction, instructional strategies, school context, etc.). These forms of teacher knowledge are embodied and interwoven in the varied acts that make up instruction, and as such are difficult to fully explicate, let alone measure. In addition, the practices that make up the instructional activities are presented in a logical order, but the practices themselves are intended to respond to students' ideas and experiences, and as such, cannot be specified as a sequence of teacher actions. And finally, what is clear when we look across the four sets of practices we present in the following sections is the issue of grain size. Some practices could arguably be considered composites of smaller scale practices, each with important subgoals for participation and learning that require particular kinds of guiding principles, teacher knowledge, tools, and student involvement. Other practices may seem too limited in scope. We do not attempt to resolve the issues about the granularity of teaching practices here,

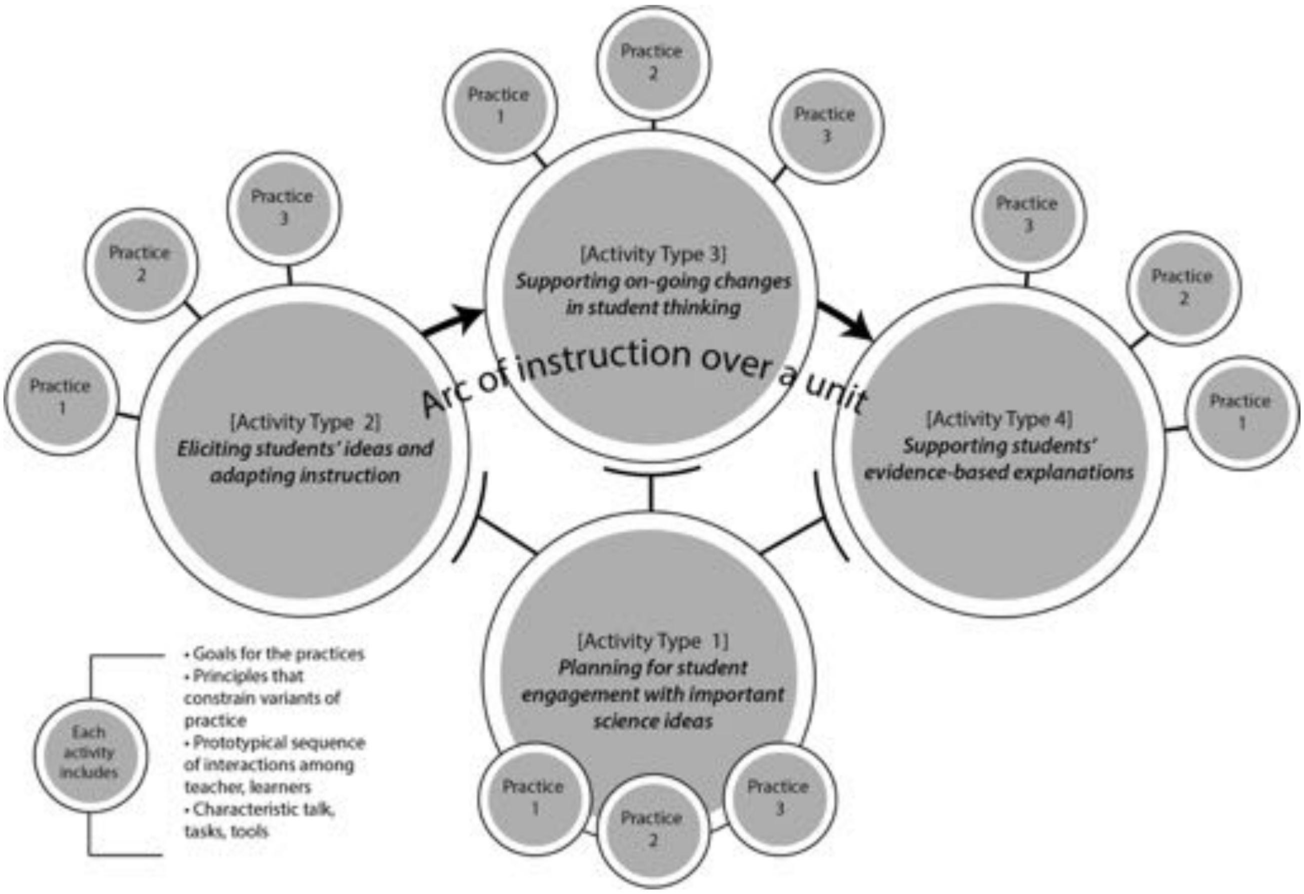

Figure 18.1. Fundamental teaching activities as "containers" for four sets of core practices. Activities and practices build upon one another to support valued forms of work by students.

but acknowledge that the improvement of instruction will rely, at least in part, on identifying what level of classroom activity is worth focusing on and, just as important, how these practices work together to support student learning.

Translating Scholarship to Practices: Planning for Students' Engagement With Important Science Ideas

Preparing what to teach and how to teach subject matter shapes students' opportunities for learning. Reflecting this stance, the research field has largely shifted from the perspective of teachers as uncritical consumers of curriculum to teachers as active learners who draw on their prior experiences making sense of instructional materials, unpacking ideas, and reconstructing lines of activity for their students (Lobato, 2003; Marton, 2006). In the process they interrogate the curriculum, seek out complementary resources, collaborate with colleagues, and solicit opinions on their emerging designs for units of instruction (Davis & Varma, 2008; Sinha et al., 2010). A rote implementation of common curriculum activities is widely viewed by the research community as ineffective on many levels, not least because the underlying assumption is that curriculum designers have somehow tailored the materials to meet the needs of all students, and that teachers have no specialized knowledge that bears on the design of learning experiences.

We describe here themes that characterize the literature around how teachers plan for students' engagement with science on a unit-level timescale (approximately two to six weeks). These themes include the quality of curricula, the tensions between well-designed curricula and how they are adapted for implementation, and the need to problematize subject matter, based on what we now know about learning and student identity and also based on the conceptual, social, and epistemic goals of science.

Limitations of common curricula. Common curricula and science texts have been criticized on several grounds. Project 2061's analyses of middle school and high school science texts indicated that these resources paid insufficient attention to content-related learning challenges; used inappropriate representations, which reinforced common misconceptions (Kesidou & Roseman, 2002); failed to connect abstract ideas to real-world events (Stern & Roseman, 2004); and offered little guidance to help students make sense of their experiences and observations or for teachers to monitor their progress (Stern & Ahlgren, 2002). In the United States, textbooks are encyclopedic in terms of embedded ideas, vocabulary, and sheer mass. Eighth-grade editions were found to "cover" an average of more than 65 topics in the school year, as opposed to 25 topics in the curricula of other countries (Valverde & Schmidt, 2000). More recent curriculum materials align their content with national and state standards, but they often fail to include sense-making tasks, such as building representations of micro- or conceptual-level events or contrasting science explanations with commonly held notions. Rather than beginning with compelling questions and then attempting to describe elements of what students already know, school curriculum often highlights lists of information—for example, the organelles that make up a cell, the parts of the water cycle, or characteristics of the states of matter—ideas that appear to most learners as unrelated facts. This inability to support sense making was also documented by a consensus report on curriculum use in Europe. Science materials there appear most often as catalogs of discrete ideas, lacking coherence or relevance to each other (Claxton, 1991; Lyons, 2006; Osborne & Collins, 2001).

There is an implicit theory of action in many curricula, which is reflected in the design of instruction—that of "giving students the basics," which are sets of facts and lower level skills that must be mastered before engaging with ideas of any authentic complexity. This reductionist logic, however, is unsupported by research (Chi, 2000; Clark, 2006; Linn, Davis, & Eylon, 2004). According to a wide variety of studies, the process of learning (in this case, from the cognitive perspective) is not one of "adding information" or absorbing understanding from hands-on activity, but of constant conceptual restructuring (diSessa, 1993; Parnafes, 2012). This is a nonlinear process that reflects the interplay of both students' intuitive ideas and instructed ideas. The research synthesis volume *How People Learn* (Bransford, Brown, & Cocking, 2000) states in unequivocal terms that learning is facilitated when the subject matter is *situated in phenomena or problems that are highly contextualized*, when it is presented at an *appropriate level of complexity*, and when students find it *initially comprehensible*. This rich context serves several functions: It stimulates in students a "felt need" to understand new concepts and disciplinary practices that can help them navigate the problem space; it supports a sense of purpose and challenge for students; and it acts as a framework to organize students' reasoning about how ideas used to solve the problem are related to one another.

Not all curricula are disconnected from a clear vision of learning. Some focus on learning goals found in standards and also use innovative, research-based approaches to teaching that engage learners in scientific practices. These curricula are conceptually coherent, meaning the materials align with learning goals that are based on a set of pivotal scientific ideas while avoiding nonessential information; facilitate connections between new ideas and prior knowledge; and connect activity to scientific ideas (Kali, Linn, & Roseman, 2008; Roseman, Linn, & Koppal, 2008; Shwartz, Weizman, Fortus, Krajcik, & Reiser, 2008). Examples of successful curriculum (in terms of student learning) in the literature can set complex ideas within everyday contexts for students. Nordine, Krajcik, & Fortus (2011) argue that in order for students to activate, reorganize, and make connections to their existing ideas, they must be pressed to think analytically about familiar phenomena—"Why is asthma so common in my neighborhood?" or "Why do I have to wear a helmet when I ride my bike?" These authors suggest that it is within these everyday situations that students' initial working theories were formed and where they most conspicuously apply. The introduction of new science concepts to students' reasoning about familiar contexts, then, can help students better understand how the theories they learn in school have broader explanatory power than their initial ideas, and they can adapt their thinking accordingly (Linn & Hsi, 2000; Roseman et al., 2008; Shwartz et al.). We note, however, that students' personal familiarity with a context or phenomenon has not been empirically established as a necessary condition for engagement and learning. There are, for example, productive cases of teachers asking students to do thought experiments in which the circumstances under consideration were apprehensible by students but did not map onto their real-life experiences. In such instances, students imagined the effects of ecosystem disturbances (Lehrer, Schauble, & Lucas, 2008) or were asked what would happen to the reading of a spring scale with a 5-kilogram mass attached if it were placed under a glass jar and air inside evacuated (Minstrell & Kraus, 2005). There is a clearer consensus about conditions that inhibit engagement. Students have more difficulty learning, for example, if the subject matter is presented only as abstractions (including excessive vocabulary or mathematical symbolism), if scenarios for study are stripped of context, if learning experiences seem unrelated to one another, or if situations referenced in the learning tasks require cultural knowledge that students are not familiar with.

Adapting curricula for teaching. What teachers do with instructional materials is enormously consequential to student learning. Adaptation, however, cuts both ways. Some studies describe maladaptive changes by teachers to the intent of curricula, and other studies suggest that principled adaptation is as important as the initial quality of the materials themselves (Penuel, Fishman, Gallagher, Korbak, & Lopez-Prado, 2009; Rivet, 2006).

Beginning with the challenges, even with high-quality curricula, teachers may be unable to understand the design rationale for particular activities (Davis & Varma, 2008; Songer, Lee, & Kam, 2002), to understand their roles and their students' roles in the prescribed activity structures (Enyedy & Goldberg, 2004; Spillane & Jennings, 1997; Tushnet et al., 2000), to use recommended strategies for engaging students in science discourse (Alozie, Moje, & Krajcik, 2010), or to distinguish coherent from incoherent sequences of activities (Lin, 2008; Lin & Fishman, 2004). It is unclear from the current literature whether teachers have difficulty understanding how activity might be enacted in the classroom or if there are institutional norms and expectations that constrain their instructional choices. For example, working with teachers in a high-needs school to implement a curriculum focused on evidence-based explanation, McNeill and Pimental (2010) observed participants repurposing the curriculum to be less cognitively demanding in order to prevent student failure. Tasks that initially required students to practice complex problem-solving skills became tasks that merely required guessing the correct answer.

Under supportive conditions, there are benefits to teachers' thoughtful adaptations of curriculum. In one of the few comparison studies of curriculum use by teachers, Penuel, Gallagher, and Moorthy (2011) found that in terms of student gains, the most successful middle school earth science teachers needed access to high-quality curriculum materials, but, just as important, they needed professional development that helped them plan for principled adaptation of those materials. This empirical work supports arguments by others that coherent policymaking in science education should encourage teachers' selective use and adaptation of teaching strategies and high-quality materials to improve science learning (M. W. Brown, 2009; Cochran-Smith, 2003; D. K. Cohen, Raudenbush, & Ball, 2003). Such high-quality materials may include educative curricula (see Davis & Krajcik, 2005). These curricula are designed to promote teacher learning as well as provide a scope and sequence of student activity. The materials support subject matter knowledge, pedagogical content knowledge for topics, and pedagogical knowledge for disciplinary practices used in the curriculum.

There is evidence that when teachers are able to simply select important content ideas from the curriculum, this sets the stage for them to design or modify learning experiences with more coherence and purpose. In a study focusing on this phenomenon, K. Roth et al. (2009) worked with groups of teachers to develop science content story lines from their curricula. In the classrooms these story lines played out via several connected instructional strategies, for example, focusing on one main learning goal, setting the purpose with a focus question, selecting activities and representations that were matched to the learning goal, linking ideas and activities logically, and summarizing and synthesizing key ideas (Kesidou & Roseman, 2002; Roseman, Kesidou, & Stern, 1996; K. Roth et al., 2006; Stern & Roseman, 2004). The researchers found that students' learning increased significantly in four different content areas after their teachers participated in the program. Student learning was predicted not only by teachers' science content knowledge but also by their ability to analyze science teaching in terms of student thinking and learning, as well as by their use of content story line teaching strategies. These findings are consistent with those of Rosebery et al. (2010), who found that when teachers select which curricular ideas will become focal, this appears to open the door for other productive design moves. In their study, identifying such a core set of ideas helped teachers (1) review their own understandings of these phenomena and their interrelationships, (2) select appropriate learning materials while discarding activities that were inconsistent with the core ideas, and (3) design activities that would bring everyday and scientific meanings into contact (in this case, investigating the effect that wrapping an ice cube in a winter coat would have on its melting).

Identifying important science ideas from the curriculum is not intuitive, especially for beginning professionals. Without training, novice elementary and secondary science teachers tend to select activities uncritically and take mundane curricular topics (e.g., "glaciers," "sound," or "solutions") at face value without seeking deeper or more comprehensive scientific ideas that could help students make sense of the many activities prescribed in support materials (Abell, Bryan, & Anderson, 1998; Davis, Petish, & Smithey, 2006; Mikeska, Anderson, & Schwarz, 2009). For example, in a classroom study of beginning secondary science teachers, Windschitl, Thompson, Braaten, and Stroupe (2012) found that the overwhelming majority of novices either adhered to their activity-centered curricula or else merely altered minor lesson details. It is important to note that researchers discovered that for these novices, identifying a "big science idea" was a critical precondition to trying out sophisticated forms of instruction. In fact, no participant who didn't reconceptualize a curriculum topic as a big idea switched later on in the unit to ambitious teaching. Taken together with the findings by Rosebery et al. (2010) and K. Roth et al. (2009) it appears that the intellectual work of defining focal ideas for instruction has payoffs for other kinds of pedagogical decision making during instruction, and that overlooking this step compromises the quality of subsequent instruction.

Summary. There is strong evidence that the primary resource for the design of instruction—a common curriculum—is limited in terms of its consistency with research on learning. The "begin with the basics" approach, for example, has weak backing in the literature when compared with situating content in contexts that are complex and rich with interwoven science ideas. This is in addition to the well-known problems of textbooks being encyclopedic in the volume of ideas presented and kit-based curricula incorporating far too many activities. Although some high-quality curriculum exists, it appears to be crucial that teachers also develop the capacity to adapt these materials to the needs of their students and to the affordances of their local contexts. We know little of how teachers engage in these complex practices. We do know that teachers should design for a series of connected ideas and experiences around a set of fundamentally important science concepts, but how teachers reason with and about subject matter knowledge is poorly understood. In the second decade of the 21st century, we do not even have a basic understanding of the relationship between teachers' subject matter knowledge and teaching itself. Deep knowledge is likely important for any form of excellent teaching, but how this is coupled with an understanding of student thinking and curricular aims is uncharted territory. There is little acknowledgment of how teachers learn in the process of adapting curriculum—and not just about the strategies of adaptation, but about the science content itself and about pedagogy. Almost completely absent from the literature are accounts of how *groups* of teachers work together to shape instructional experiences for students and use their collective professional resources to improve. Broad research questions that remain unanswered include the following: How do teachers reason with curriculum materials and other resources to design instruction? How is the design of curriculum, in particular the driving questions and the central phenomenon under study, related to sustained student engagement with the ideas? And how can curriculum be designed that incorporates pedagogical guidance about being responsive to students' ideas as instruction unfolds?

Example of a set of core practices around planning for students' engagement with important science ideas. We will use the previously described literature on planning for engagement to introduce the first "candidate practices" that might be considered core to the repertoire of ambitious teaching. These practices are designed to sequence instruction in a way that engages students with important science ideas. If we stay faithful to the learning goals described in documents such as *Taking Science to School* (NRC, 2007) and the *Framework* document for the Next Generation Science Standards (NRC, 2012) and to evidentiary warrants in the literature, then a unit of instruction would be based on complex situations involving natural phenomena as the objects of explanation. And if understanding the nature and development of scientific knowledge—which includes the development of the explanation itself—is an explicit target of instruction and not just an assumed by-product of classroom talk, then much of the knowledge would be developed through engagement in scientific practices. And finally, if an understanding of the development of scientific knowledge is important, then a prototypical unit would involve, at a minimum, the iterative, public, and principled critique of explanations by students, and teachers then would attend to and support this work as a primary feature of professional practice. This, in effect, frames teaching as "working on students' ideas."

To set the stage for these experiences, teachers must plan for them with their peers. Teachers' planning practices, as described in Table 18.1, are designed as a collaborative interrogation of science ideas that are presented in common curricula, along with an analysis, reconstruction, and reorganization of these ideas, keeping in mind the kinds of reasoning students would have to do in order to engage deeply with them. We assume a reasonable set of constraints for this planning practice—for example, teachers often have a matter of weeks to work with students on a cluster of related science ideas (e.g., gas laws, energy movement within ecosystems, what causes the seasons, etc.). We describe the goal of the overarching planning activity and its underlying principles. We then outline a prototypical sequence of practices that is characterized by particular tasks and shaped by the use of specialized tools (see Figures 18.2 and 18.3) and talk.

These particular tools were used for planning a high school unit on gas laws (the tools for this and the three other situated examples in upcoming sections were created and used by teachers who have worked with the first author). Figure 18.2 depicts an activity in which a group of teachers wrote on note cards what they perceived to be the main ideas listed in their curriculum and in the standards. They arranged the cards on a table and negotiated with one another which ideas had the greatest explanatory power (moving them to the center), which ideas were linked to these, and which appeared more peripheral (moving them off the table). The ideas that were moved to the center became the focus of the unit, and teachers then unpacked these ("What is the role of heat energy in kinetic molecular theory?") in preparation for the next phase of planning. Figure 18.3 is a planning tool the teachers used to coordinate an anchoring phenomenon that students could explore with a thorough causal explanation for this event—in this case, the event was the mysterious implosion of a railroad tanker car after it was steam cleaned. Each conceptual segment of the explanation was then linked with an activity or reading that students would do during the unit. These learning activities were laid out in roughly chronological order (shown on the right side of Figure 18.3). These tools helped the teachers focus instruction on "big" science ideas, and helped them align

TABLE 18.1. Planning for Student Engagement With Important Science Ideas

Goal:

To develop a coherent, challenging sequence of instruction that is aligned with standards and involves students in scientific practices aimed at using, developing, testing, and revising explanations for natural phenomena.

Principles:

- All curriculum requires adaptation, in part to link the science ideas with experiences, interests, and knowledge that students currently have and to use local resources for instruction.
- A top-level goal of the unit is to build toward an evidence-based explanation of a scientific phenomenon.
- Learning should be situated in and organized around complex questions or problems that students can relate to and that require the integration of different forms of knowledge.
- Learning experiences and activities must be sequenced to contribute to an understanding of the anchoring phenomenon.
- The teachers' own understandings of the subject matter must be interrogated with peers and refined through the process of planning.

Prototypical sequence of tasks and talk:

Practice 1 Principled deconstruction of curricular ideas

Teachers lay out the curricula, relevant standards, and other resources. In the initial conversation, two questions are considered. These address different aspects of planning, but in this professional practice they are considered simultaneously.

- What standards should we attempt to address in this curriculum?
- What ideas in the curriculum have the greatest explanatory power and should become the focus of students' ongoing efforts at understanding?

Practice 2 Articulating the anchoring phenomenon and its underlying explanation

2a. Problematizing the content. Once a central set of ideas is tentatively identified, the group considers how the content can be problematized. The questions that are addressed here follow:

- How can these science ideas be embodied in a phenomenon that is related to students' experiences or interests, or that they find compelling for other reasons?
- How can the phenomenon or scenario and the questions asked about it be made appropriately complex, matched to important learning goals, and engaging for students?

2b. Developing the causal explanation. When a sufficiently complex anchoring phenomenon is identified, the teachers then collaboratively create a fully elaborated causal explanation for it, which links observable and unobservable events. Questions asked here include the following:

- What gaps do we have in our own understanding?

Practice 3 Organizing the scope and sequence of learning activities around the big ideas

3a. Matching ideas to activity. The causal explanation is separated into constituent ideas, which are matched to curricular activities and ideas students need to engage with. Questions asked here include the following:

- How can the learning experiences be cumulative and coherent?
- Which activities and ideas are not matched to the big science ideas and thus should be discarded?
- How will we teach important science ideas in this unit that are not directly connected with our anchoring phenomenon?

3b. Science practices. Teachers consider how an ensemble of scientific practices can produce, test, and evaluate hypotheses generated within the context of the anchoring phenomenon. Teachers decide what science practices students should engage in and in what ways—in particular, modeling and explanation.

3c. Culminating assessment. Teachers develop an outline for final assessment. Questions here include the following:

- How can the explanatory models developed by students be products of genuine understanding and not the reproduction of textbook explanations?
- How can ideas learned be applied to new scenarios?
- How can we support both collaborative work and individual accountability?

activities for students with ideas that, taken together, constituted an evidence-based explanation of the anchoring phenomenon.

Translating Scholarship to Practices: Eliciting Students' Ideas in Order to Shape Instruction

An important goal of teaching in science is to help students refine their thinking about the natural world. Relevant to this undertaking is one of the most robust findings in all of educational research—that what students already know about the subject matter has an enormous influence on how they respond to instruction and what they eventually learn (Ausubel, 1968; Bransford et al., 2000; Gage, 2009). It seems logical, then, that teachers should cultivate practices that reveal students' existing ideas and, just as important, their *ways of reasoning* about phenomena. Until recently, students' ideas were not treated this way.

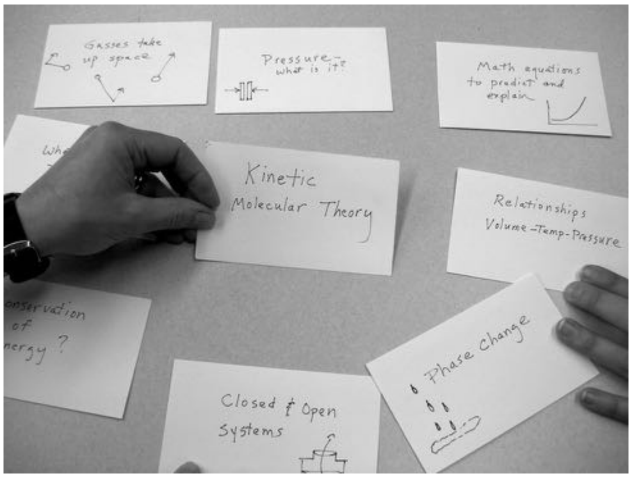

Figure 18.2. Card sort activity for teachers to prioritize science ideas from the curriculum with the greatest explanatory power. This example is from collaborative preparation for a Gas Laws unit in high school.

Post-*Sputnik* science education literature barely acknowledged that students came to the classroom with conceptions relevant to the curriculum. But by the 1980s, new theories had developed around the assumption that children's minds are at work outside school hours and often on science-related ideas. This began a wave of studies about students' conceptions regarding every scientific phenomenon imaginable (Anderson, 2007). Theories about children's ideas gradually evolved from descriptive, to explanatory, to instructionally prescriptive (Hewson, Beeth, & Thorley, 1998; Posner, Strike, Hewson, & Gertzog, 1982). Eliciting what students think became important, but it was couched in terms of revealing prior conceptions about natural phenomena, which would often require special forms of remediation; this weak form of attention to student ideas is alive and well today in the form of pretests. Although limited in their aims, strategies developed during this time began to signal that teachers should be *interacting with students' ideas* during instruction, rather than merely evaluating them.

The focus on revealing and confronting errant learner conceptions gradually shifted, first to a recognition that in the mind of the learner, his or her preexisting conceptions were plausible and, even though fragmented or inconsistent in application, had explanatory power in familiar, everyday contexts (NRC, 2005; J. P. Smith, diSessa, & Roschelle, 1993). But even this literature tended to focus on distinctions between students' conceptions and experts' conceptions, without considering the full array of cognitive, linguistic, and experiential resources that students bring to the classroom (Atwater, 2000; diSessa, 1993; Louca, Elby, Hammer, & Kagey, 2004; Metz, 1995; Metz, 2004; Tytler & Peterson, 2004) and how these might be put

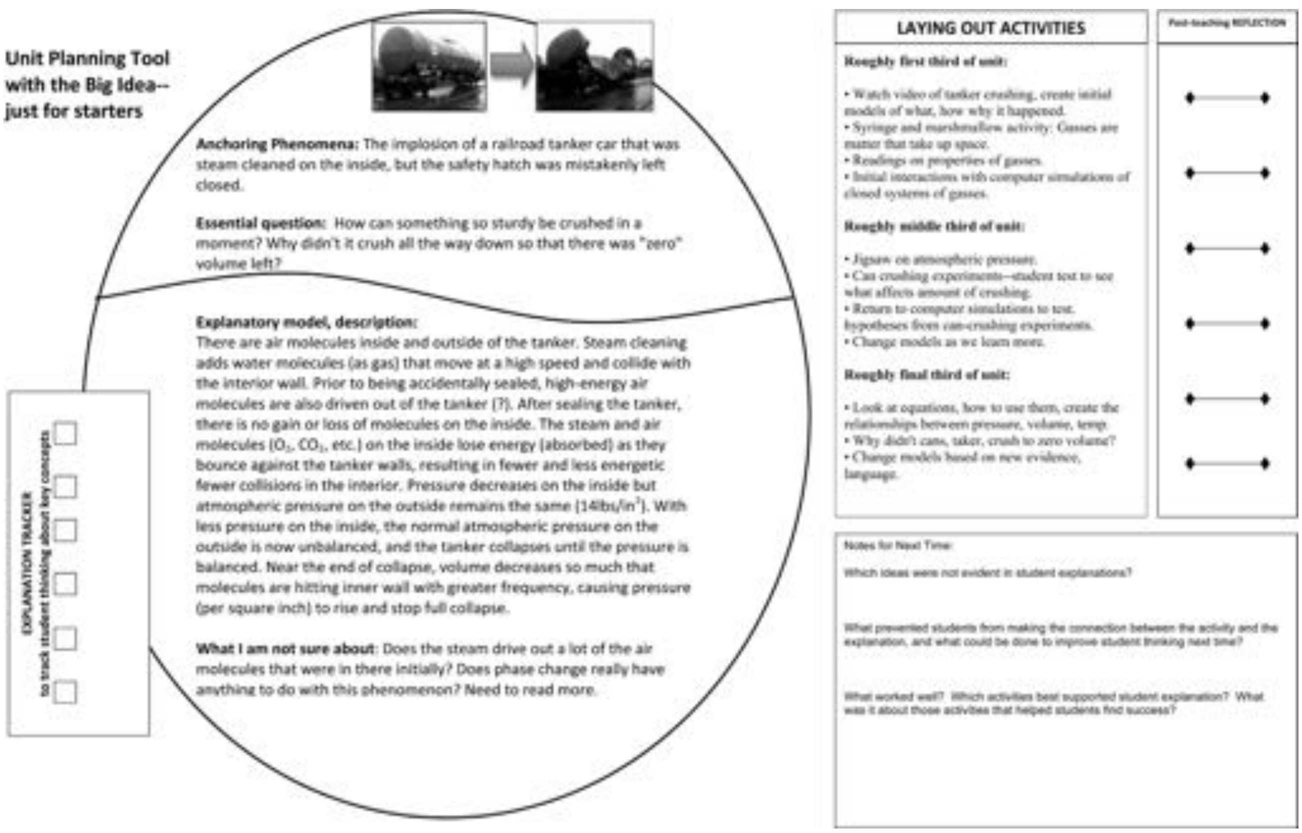

Figure 18.3. Tool for organizing and planning curricular activities around a complex phenomenon (in this case an imploding railroad tanker car) and its underlying explanatory model. This example is from a high school Gas Laws unit.

to use in creating more coherent and flexible theories about the world (Danish & Enyedy, 2006; Hammer & Elby, 2002; Tang, Coffey, Elby, & Levin, 2010).

The idea of "resources" that students bring with them to the classroom now appeals to the research community because it acknowledges a broad range of assets that students work with in developing their own understandings. Maskiewicz and Winters (2012) describe one class of resources as concrete, phenomenon-specific intuitions and experiences, which can serve as referents to inform class-constructed scientific theories (diSessa, 1993). Other resources are epistemic (e.g., that knowledge about the natural world can be constructed rather than received from authority figures) and are hypothesized to support the ability to participate in activities related to the generation of knowledge (e.g., analogy work, argumentation, or modeling) that can guide the direction of the classroom's inquiry activity (Hammer & Elby, 2002; Louca et al., 2004; May, Hammer, & Roy, 2006). Maskiewicz and Winters use the term *resources*—rather than *expertise*, *knowledge*, *beliefs*, *skills*, or *conceptions*—to emphasize that students' contributions are often composed of small, unconnected, context-sensitive ideas, which can, with instructional guidance, serve as building blocks for productive theorizing. Students' ideas are resources not just for teachers but for their peers as well. To be used as such, their thinking has to be made visible to others (Danish & Enyedy, 2006; Linn & Hsi, 2000; Radinsky et al., 2010), and teachers have to help everyone in the classroom develop the habits of appropriating and critiquing the partial understandings of others.

Being responsive to what students bring to the classroom is now viewed as fundamental to effective teaching. *Responsiveness*, however, has several meanings, some of which do not necessarily advance the goals of ambitious teaching. It can mean showing respect for students' ideas, letting all students have a chance to share their thoughts, or being affirmative in classroom conversations. These moves can be seen in the TIMSS Project videos of five U.S. science classrooms (K. Roth et al., 2006). Each teacher is indeed respectful of student contributions, but in the videos there are no instances in which a teacher (or peer) treats a student's idea as a resource for the class to think about. Instead, students' questions are treated as requests for information—queries that should immediately be answered (or otherwise dispatched, so as not to disrupt the flow of instruction). *Responsiveness* is still conceptualized vaguely in the literature and is in need of a more explicit definition, one that is congruent with ambitious teaching. Pierson (2008), for example, characterizes *responsiveness* as the ongoing "attempts to understand what another is thinking, displayed in how a conversational partner builds, questions, probes, clarifies, or takes up that which another has said" (p. 25). A responsive classroom is guided in part by the ideas, questions, and everyday experiences that students relate to the subject matter. The responsive teacher listens carefully to student talk, considers how to represent ideas publicly for examination by the whole class, and assesses what instructional moves might be warranted by the ideas in play. The expert practitioner, on the other hand, is becoming defined, in part, by the ability to turn over this kind of intellectual work to students by having them consider, respond to, and challenge each other's ideas (Lampert, 1990; van Zee, 2000).

The importance of discourse. The dialogue referred to in the preceding section is not natural for students or teachers; it requires social arrangements and new patterns of talk that facilitate sharing and critique. There are a number of examples in mathematics, science, and literacy in which teachers use responsive strategies to transform how children talk and interact, ultimately affecting what they learn (Ball, 1993; Jacobs, Lamb, & Philipp, 2010; Pierson, 2008; Sherin & van Es, 2009). From an equity perspective, teacher moves such as eliciting students' ideas, prompting students to compare their ideas with those of others, asking students to explain their reasoning, and asking students to reflect on their current state of understanding have led to students' deeper engagement with the content (Atwater, 2000; Duschl & Duncan, 2009) and to sophisticated reasoning by learners who do not typically participate in the academic life of the classroom (Chapin & O'Connor, 2004; Cobb, Boufi, McClain, & Whitenack, 1997; Lampert, 2001; C. D. Lee, 2001; Thompson, in press).

A responsive environment cannot be created without specialized repertoires of talk. It would be difficult to overstate the importance of the role that discourse is now recognized to play in all aspects of science instruction. Recent research in the areas of student learning, expert teaching, and knowledge construction in the disciplines has converged on the notion of classrooms as communities in which the careful orchestration of talk by teachers mediates increasingly productive forms of reasoning and activity by students (Engle, 2006; Leinhardt & Steele, 2005; Minstrell & Kraus, 2005; Mortimer & Scott, 2003; Sfard & McClain, 2002). In this view, sense making and scaffolded discussion, are "the primary mechanisms for promoting deep understanding of complex concepts and robust reasoning" (Michaels, O'Connor, & Resnick, 2008, p. 284).

This discursive mediation is also critical for engaging learners in the characteristic practices of the discipline, which are "to formulate questions about phenomena that interest [students], to build and critique theories, to collect, analyze and interpret data, to evaluate hypotheses through experimentation, observation and measurement, and to communicate findings" (Rosebery et al., 1992, p. 65). When students are allowed some control over discussions, and are scaffolded to engage with one another in productive ways, they determine the range and flow of ideas, explore their emerging understandings of the scientific question under study, and are able to "go public" with confusion. Driver, Leach, Millar, and Scott (1996) observed that "[s]tudents benefit from considering a range of ideas that their classmates may have to describe the same phenomenon and developing ways of evaluating these explanations. Through such interactions, students can come to appreciate the criteria on which judgments in science are made" (p. 22).

The positive effects of productive discursive practices on science learning and achievements of all students, particularly those of nondominant groups is well documented (Ballenger, 2009; Gallas, 1995; Hudicourt-Barnes, 2003). These forms of discourse are rare, however, even in the classrooms of experienced teachers (Alexander, Osborn, & Phillips, 2000; Banilower, Smith, Weiss, & Pasley, 2006; K. Roth & Garnier, 2007; Weiss et al., 2003). Teachers often dominate the talk and thus reduce their own opportunities to learn about how their students are thinking and what resources they are reasoning with. In common practice, students are rarely asked to substantively engage with one another's ideas (e.g., Herrenkohl, Palincsar, DeWater, & Kawasaki, 1999; Hogan, 1999; Lemke, 1990). This inhibits their willingness to do so when put in situations that would otherwise facilitate these interactions (Hogan & Corey, 2001; Rosenberg, Hammer, & Phelan, 2006).

All this suggests that teachers who want to "work on students' ideas" require not only specialized forms of content knowledge, discourse skills, and a working relationship with students, but also a student-thinking lens on their own practice. A growing body of literature suggests ways to accomplish this (Brookline Teacher Research Seminar & Ballenger, 2003; Rosebery & Warren, 2008). But as we noted earlier, large-scale observational studies indicate that most teachers are currently not eliciting students' ideas or experiences as resources for instruction. As with other aspects of ambitious teaching, this is not surprising, because likely they have never seen it modeled, it is not typically part of teacher training, and these nuanced and interactive moves can hardly be specified in curriculum materials. Even with extensive training, many teachers, both experienced and novice, remain unable to use students' ideas (Penuel et al., 2009; K. Roth et al., 2009; Thompson, Windschitl, & Braaten, 2013). This points to some of the most important unanswered questions in science teaching research: How and why do teachers take up a student thinking focus? What does it afford them in their practice, and what are the implications for student learning over time? Why are some teachers able to take up such a perspective, while others appear unwilling or unable to do so?

The role of teacher knowledge. Although teacher knowledge plays a role in responsive instruction and ambitious teaching in general, its nature and use are not well understood. Pedagogical content knowledge (PCK) is frequently mentioned as a resource for decision making, and several research programs have investigated its role in instruction. The construct of PCK, however, is still being defined in terms of the types of understanding it encompasses. On one hand, it has been broadly described as an amalgam of subject matter knowledge, pedagogical knowledge, and knowledge of the teaching context (Gess-Newsome & Lederman, 1995). On the other hand, it is increasingly being seen as specific to each domain, topic, student, and situation (see Abell, 2008; Sadler, Sonnert, Coyle, Cook-Smith, & Miller, 2013; Van Driel & Berry, 2012). For example, the pedagogical task of helping students represent an initial set of hypotheses about some phenomenon depends not just upon teachers' subject matter knowledge, but also upon specific learning goals for that lesson, knowledge of how familiar the students are with the types of discourse and idea sharing involved, and how this representation might be used in subsequent class periods. Several fundamental questions relevant to the study of teacher knowledge currently face the field. Should we focus on knowledge as a set of schema one possesses and elaborates on over time, or would it be more illuminating to study how teachers reason with various resources about pedagogical decisions? To what degree are teachers' decisions drawn from an existing repertoire of alternatives versus constructed on the spot? How does this ability develop, and can it be supported by means other than the accumulation of practical experience? These questions highlight where the field lacks longitudinal studies of teacher practice. We will not attempt to characterize further the research on teacher knowledge, except to suggest that from a teaching-as-practice perspective, it may be informative to concentrate studies on the enactment of core practices, rather than try to catalog the knowledge required for every conceivable interaction an educator might have with learners.

Summary. The field is moving from an image of teaching as revealing and remediating students' everyday conceptions to one of uncovering a broader range of resources that students bring to the classroom and using these to support knowledge building by the classroom community. In this view, the competent teacher is not one who merely "hooks" students or "gets them excited about science" but one who elicits a variety of experiences, ideas, and ways of reasoning that learners use to make sense of some event or question. The teacher then makes strategic adaptations—both in the moment and over the long term—to exploit these resources in the knowledge-building activities that follow. The demands on the teacher's skill here are substantial, and the research, in sum, strongly suggests that new images of expertise around these capabilities are emerging. Early in a school year, for example, teachers would need to help students understand how knowledge is produced in science and to develop the social norms that would support these activities in their classrooms. At the beginning of each unit of instruction, teachers would have to craft ways for all students to have initial access to complex science ideas, and in the process teachers would have to manage diverse forms of talk that allow students to exchange ideas. Teachers would employ strategies to make key parts (but not all) of student thinking visible and public, and then consider how to respond to these ideas as they adapt instruction for the next few days. Clearly, the skills required for ambitious teaching are more sophisticated, are more flexible, and are grounded in deeper subject matter knowledge than in traditional conceptions of the competent professional.

Example of a set of core practices around eliciting students' ideas in order to shape instruction. Many questions remain unanswered about how teachers uncover and use students' ideas to guide instruction, but we do know enough about what is productive in the classroom to represent key pieces of the knowledge base as "candidate" core practices that work together (see Table 18.2). Our description for the overarching purpose of these practices is "eliciting students' ideas in order to shape instruction." These three practices are (1) eliciting students' ideas, (2) making thinking visible by representing publicly selected elements of students' ideas (see Figures 18.4 and 18.5), and (3) adapting further instruction based on the partial understandings students have of the content. These practices likely would be enacted at the beginning of a unit of instruction, but teachers' elicitation and adaptation moves would continue to be used throughout the learning experience. Also, implementing these strategies presupposes that the teacher has already identified in the curriculum the key scientific ideas and an anchoring phenomenon of sufficient complexity and richness to sustain students' intellectual engagement throughout a unit (the planning practices previously described).

Reading our description, it will again become evident that the "grain size" of a teaching practice is undefined by the field. As with our previous example of a practice, this rendering is necessarily simplified, but does include a sequence of tasks, talk, and tools, which can be shared, tested, and modified (based on evidence of students' participation and learning) by a community of practitioners.

These figures come from a third-grade unit on sound. The phenomenon anchoring the unit was a video of a singer who was able to shatter a wineglass using the energy of his voice. Figure 18.4 shows a "before-during-after" tool for students to record observations and initial hypotheses about the video. This tool provided a scaffold for student reasoning and made thinking visible, so that students could compare ideas with one another. The tool shown in Figure 18.5 was used during the same class period. After students had done a gallery walk, looking at each other's initial models, the teacher called them back to the whole-group setting. She asked students what theories were described in the models they saw. The teacher, with students' assistance, decided on five partial theories and how they could be stated. This tool helped to make the thinking of more members of the class visible; it also organized and consolidated a range of ideas in one place for future reference. This tool remained on a classroom wall throughout the unit. In the following weeks, the space under each theory was eventually filled with note cards, written by students, describing whether an activity, experiment, or reading supported or disconfirmed that particular idea (see also Zembal-Saul, 2009).

Translating Scholarship to Practices: Supporting Ongoing Changes in Student Thinking

In this section we explore teaching practices described in the literature that support progressive changes in student thinking and participation across a unit of instruction. We assume here that teachers are anchoring the instruction in a complex problem, that they have elicited students' initial ideas, and that they have found ways to respond to the resources that students bring to learning this particular set of ideas. With these preconditions, the important questions are these: What intellectual work will be valuable for learners to engage in on a regular basis? What is the purpose of these activities? What frameworks exist for designing this work? Nearly all lines of research that are successful in documenting robust and equitable forms of learning depend upon practices that constantly monitor changes in student thinking about selected facets of a complex problem or question. These changes are prompted by new observations, new ideas, and the logic expressed by others in the classroom, not merely by exposure to material work. To facilitate such changes, teachers use repeated cycles of similarly structured activity, and often revisit the overarching problem of the unit to apply what has been learned (i.e., teachers take stock of where students are currently, they introduce new ideas and experiences for students to reason with, they prompt reasoning and asking testable questions, and they support students in linking ideas with the larger phenomenon that is anchoring the unit of instruction).

The larger aim is not just to refine a particular idea or move toward a particular solution to a problem, but also to develop more capable thinkers over time (i.e., increasingly independent of overt guidance by the teacher) by helping students understand how to frame problems, use various social and conceptual resources, and monitor their own progress toward understanding. This broad vision is shared by a number of prominent frameworks for the

TABLE 18.2. Eliciting Students' Ideas in Order to Shape Instruction

Goal:

To reveal, on the social plane of the classroom, a range of resources (conceptual, experiential, epistemic, cultural, and artistic) that students use to initially gain access to a set of science ideas, to activate prior knowledge about the topic, and to use this information to shape further instruction.

Principles:

- Young learners have a range of resources they can use to communicate about and make sense of phenomena.
- Discourse is the primary social mediator of reasoning.
- For the class to "work on students' ideas," current thinking must be made visible and public.
- Eliciting traces of students' reasoning provides greater insights and instructional leverage for teachers than does the elicitation of products of reasoning ("answers").
- Adapting instruction means responding to students' intellectual needs by engaging resources they bring to the learning enterprise in order to understand challenging material.
- The trajectory of an effective curriculum is determined by both subject matter considerations and by adaptations to instruction, based on the current reasoning and resources employed by students.

Prototypical sequence of tasks and talk:

Practice 1 Eliciting students' ideas

1a. *Initiating a conversation*. A typical sequence might begin with the teacher sharing a story, showing a video, or doing a demonstration that is related to the anchoring phenomenon for the unit. Initial questions are posed, which allow access to the conversation, such as those that depend only on observation rather than conceptual understanding. "What do you see happening?" or "Have you ever experienced anything like this?" Science vocabulary is deemphasized here, and everyday language is invited.

1b. Transitioning to hypothesizing. After observations and personal experiences are shared, the teacher transitions to a set of speculative questions: "What might be going on that we can't see?" "Does anyone want to say more about this event?" "What is puzzling you?" This part of the conversation can start in small groups.

1c. Focusing on explanatory talk. Eventually, the teacher asks for possible explanations, or hypotheses, in everyday language about what might be causing the phenomenon to unfold as it does. Throughout the discussion, the teacher uses the full range of talk moves, especially those that prompt students to expand upon their thinking and to respond to the ideas of others: "How is your theory different from theirs?" "Can you tell me more about your thinking?" "Let's see if I understand what you are saying…" "What are we not sure about?"

Practice 2 Selecting ideas to make public

In the middle to latter stages of this practice, the teacher would make some form of students' thinking public. This might be a list of possible hypotheses that students expressed or a sparse consensus model in pictorial form. Both of these are community tools for further intellectual work; either one can be developed, added to, subtracted from, or reorganized by students as the unit progresses.

Practice 3 Adapting further instruction

After class, the teacher takes stock of students' contributions. He or she considers what was voiced in terms of partial understandings, alternative conceptions, and linguistic resources (academic language, everyday vocabulary, and ways of arguing) that students used to make sense of the initial puzzle or event, and everyday experiences that they related to some aspect of the phenomenon (or perhaps vicarious experiences from the media). The possibilities of working with these various ideas and experiences to develop the content story line are weighed out, based on their prevalence among the students, the enthusiasm with which students referenced these resources, and their relevance to the science itself. After this quick analysis, the teacher may decide to change the direction from which the anchoring phenomenon is approached. The subsequent sequence of instruction is, then, coproduced by the teacher and the students.

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design of learning environments, which draw from diverse literatures, including cognitive science, social psychology, science studies, and cultural anthropology.[3] Among these frameworks, or theories of instructional design, are A. Brown and Campione's (1996) Fostering a Community of Learners; Engle and Conant's (2002) Productive Disciplinary Engagement; Scardamalia and Bereiter's (2006) Knowledge-Building Environments; and Nasir et al.'s (2006) Learning as a Cultural Process. These frameworks reflect different emphases—some focus on individual reasoning and complex content, some on learner identity and engagement, some on the disciplinary basis of instruction, and some on social processes in learning. Note, however,

[3]Their similarities are not unexpected because they draw upon some comparable fundamental research bases and because they build upon one another, e.g., Engle and Conant's *Productive Disciplinary Engagement* (Engle & Conant, 2002) builds upon A. Brown & Campione's earlier *Fostering a Community of Learners* findings (A. Brown & Campione, 1996).

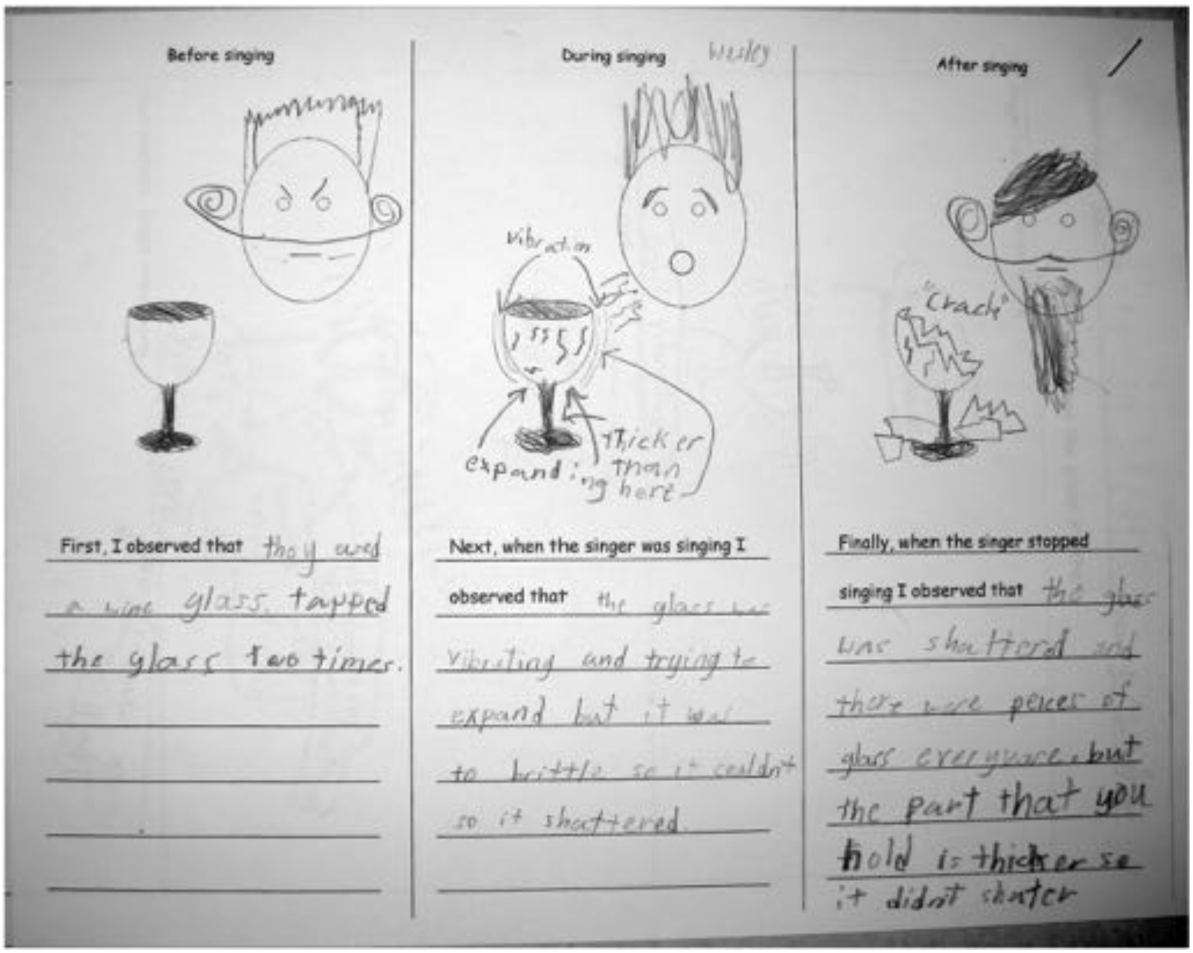

Figure 18.4. Tool to support third-grade students in creating initial models describing how a singer on video was able to make a glass shatter with his voice.

that these frameworks all recognize that students' everyday experiences, ideas, and talk about science are not obstacles; rather, this heterogeneity is the means by which the science knowledge of the collective can be elaborated upon and made more flexible and durable.

Looking across these frameworks, some commonalities are evident, not the least of which is their attention to all learners in the classroom. The principles that follow are reflected, explicitly or implicitly, in each framework. These are a subset of our previously outlined characteristics of ambitious teaching. They emphasize, in particular, principles that have been known to foster more sophisticated disciplinary reasoning, including broadening what can be used as resources, scaffolding disciplinary talk and thinking, and making ideas the objects of critique and reflection. These conditions address the goals of rigor and equity. The teacher does the following:

- Problematizes the content while making it accessible to learners.
- Makes thinking visible and public.
- Makes tools and resources available for students to use in revising their thinking, including not only instructed concepts and designed experiences but also access to the ideas, questions, and confusion of others.
- Uses discourse for its full range of productive purposes, that is, for building and reinforcing productive identities and relationships, as well as for an ongoing sharing and critique of ideas.
- Makes disciplinary norms of talk and activity explicit while holding students accountable to these norms.
- Supports metacognition in terms of students' reflection, both on their work and on their own reasoning processes, and monitoring of students' progress toward valued goals.

In the following section, we describe the instructional context into which most of the principles have been integrated. That context involves cycles of investigation and scientific modeling.

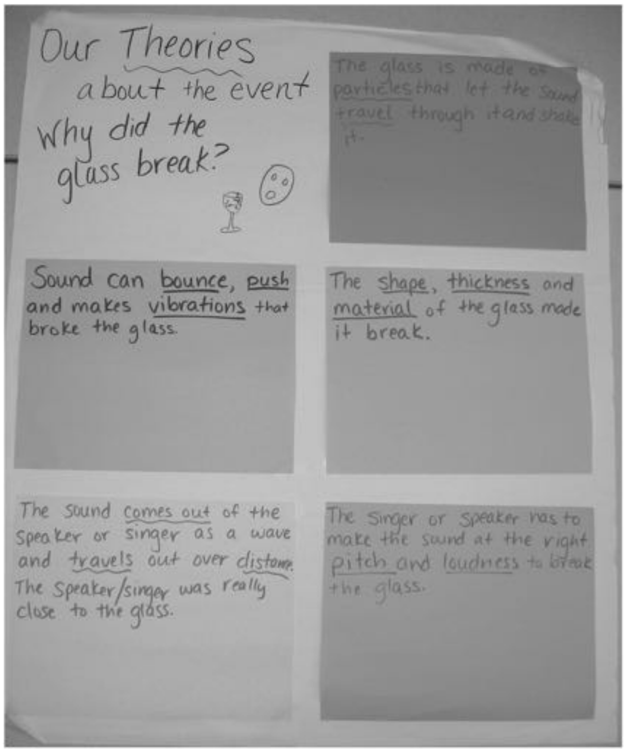

Figure 18.5. Tool to organize list of initial theories that third graders suggested regardinghow a singer could shatter a glass with the sound of his voice. This tool was eventually filled with note cards written by students, describing whether an activity or reading they did supported each of the theories.

Modeling as the larger context for advancing ideas over time. In the literature, extended intellectual work has increasingly taken place in the context of progressive modeling (which also can be conceptualized as theory change over time). In simple terms, modeling is representing a set of interrelated ideas about a natural phenomenon and then changing the relationships within the model in response to observations, new ideas, and argument. Students refine explanations using the evolving model as a tool to reason with and a set of ideas to reason about. In most classroom studies, models for model*ing* are drawn by students as roughly pictorial representations, with labels for observable and unobservable features of phenomena. These are paper-and-pencil renderings—simple technology, to be sure—but they are "owned" by students and effective for supporting concept development and reasoning. In some cases, students have created and revised other types of models, such as graphs, maps, or physical replicas, but these are not as common in the literature.

There are several reasons why studies of modeling appear with increasing frequency in the literature on science teaching. Modeling is a fundamental disciplinary activity of 21st-century science and is intimately connected with other knowledge-building practices. For example, models are catalysts for new questions and hypotheses, data from investigations are analyzed with the specific intent of filling conceptual gaps in models, and scientists use models to support claims and argue for explanations (Hempel, 1966; Knorr-Cetina, 1999; Kuhn, 1970; Latour, 1999; Longino, 1990; Nersessian, 2012; Ochs, Jacoby, & Gonzales, 1994). In accounts of classrooms that make modeling a central endeavor, scientific practices are used with models to encourage public theory-building and provide the contexts in which epistemic abilities, social skills, and cognitive capacities are developed (Duschl & Grandy, 2008; Gobert & Pallant, 2004; B. Y. White & Frederiksen, 1998).

Unfortunately, models are not typically used this way by teachers; more often they are employed to illustrate textbook ideas. Most teachers, for example, believe that models are useful only as visual aids to help explain canonical ideas to others, or to demonstrate abstractions (Cullin & Crawford, 2004; Smit & Finegold, 1995). Teachers rarely mention how models are used in making predictions or used as tools for testing ideas about targets that are inaccessible to direct observation (Harrison, 2001; Justi & Gilbert, 2002; Van Driel & Verloop, 2002). There is an awareness of the value of models in explicating science concepts but not of their value as tools for thinking about a range of phenomena or as the object of evidence-based revision. Even when teachers ask students to draw their own understandings in the forms of pictures or diagrams, such displays are disconnected from knowledge-building activity—students simply "posterize" final-form science ideas.

A very different vision of using models is expressed in several lines of classroom research, which show significant gains in conceptual learning and gains in the sophistication of epistemic practices for students over time or in comparison with students who are learning content in more traditional ways. The subject matter ranges from forces and motion to natural selection; the grade levels range from kindergarten to high school (Chinn et al., 2008; Danish & Enyedy, 2006; Gobert, 2000; Lehrer & Schauble, 2012; Passmore & Stewart, 2002; Schwarz, Reiser, Acher, Kenyon, & Fortus, 2011; Stewart, Cartier, & Passmore, 2005; B. Y. White & Fredericksen, 1998). The general pattern of instruction in these studies begins with identifying a set of important science ideas and selecting a puzzling, complex event to anchor the unit of instruction (the first set of practices described in a previous section). Students' ideas are elicited in order to adapt instruction, and then iterative rounds of activity, talk, and reasoning are designed (the second set of practices). What typically follows in teaching practice is a succession of activities for students, perhaps designing experiments, looking at secondhand data, engaging in proof-of-concept demonstrations, using media, doing readings, presentations of ideas by the teacher, various forms of small-group work, or discussion. Teachers and students regularly return to their models and assess whether changes need to be made and why.

There is nothing magical about models; in the studies already cited in this section, they are simply constructed public objects that make *changes* in thinking more visible and organized. They represent hypothesized relationships between ideas; as such, they are well suited for helping students understand complex, puzzling phenomena that require the coordination of a number of ideas, theories, facts, and knowledge of situations associated with the events or processes. There is general consensus in the literature that opportunities to explore relationships between ideas, and the contexts within which sense can be made of them, stimulates learning. For example, referring during instruction to natural events in the past and imagined future ones (something that models can support) facilitates the transfer of ideas to new situations (A. L. Brown & Campione, 1996; Cole, 1996; Forman & Ansell, 2001), as does an explicit request to make sense of larger scale science ideas by referencing smaller, component ideas that have recently been investigated, and linking multiple ideas and experiences together to understand a complex problem (Arzi, Ben-Zvi, & Ganiel, 1985; Bango & Eylon, 1997; Linn et al., 2004; Perkins & Salomon, 1988). Understanding the connections among ideas enables learners to both organize them and integrate new ideas into what they already know (Bruner, 1960; diSessa, 1993). Successful teaching supporting these integrations scaffolds frequent comparisons between ideas and assists students in reorganizing their ideas. Both of these challenges are made more tractable in modeling environments (Linn et al., 2004; Parnafes, 2012).

Productive examples of modeling in classrooms share several characteristics: (1) thinking is made visible and public with models; (2) students build into their models relationships between observable and unobservable features of events, structures, and processes; (3) models serve to connect ideas arising from *multiple* activities and investigations as students revisit and revise these; (4) teachers become more aware of student thinking and conceptual change; (5) models serve as concrete referents for students' hypothesizing and explanatory discourse; and (6) models allow students to critique one another's claims and use of evidence. What has been important in studying these classrooms is not isolating these features as variables but understanding how such conditions work in concert with one another to influence students' learning and reflection.

Models are of greatest benefit when supporting purposeful lines of talk about how evidence might change the representation. In working with seventh graders on modeling the effects of exercise on muscles, Buckland (2008) found that changes in classroom norms of discourse coincided with opportunities to generate drawn artifacts, which, in turn, supported more productive forms of whole-class argumentation (i.e., students comparing ideas about how muscles "tire out" and students challenging one another's use of evidence to support claims about the effects of exercise on muscle cells). They concluded that to advance science ideas, students need frequent opportunities to combine talk of evidence with talk about the theory that underpins their current model. K. Roth et al. (2009) found that substantial learning gains in classrooms occurred when teachers not only selected analogies, metaphors, and visual representations that were clearly linked with the learning goals, but also when they engaged students in "creating, modifying, and analyzing various representations" (p. 12). In these examples and others, working with models is tightly linked with developing explanations.

This kind of teaching requires a repertoire of discursive moves by the teacher that allows everyone to work on ideas, and in broader terms, to use talk to refine conceptual and epistemic stances toward different scientific claims. Michaels, Sohmer, O'Connor, and Resnick (2009) examined the literature on discourse and learning to extract the moves that prompt students to recognize and compare ideas and to press for explanation. These include revoicing ("So let me see if I have your thinking right. You are saying that…"), asking students to restate someone else's reasoning ("Can you repeat what she just said in a different way?"), asking students to apply their own reasoning to someone else's reasoning ("Do you agree? Why?"), prompting students for further participation ("Would someone like to add to that?"), asking students to explicate their reasoning and provide evidence ("Why do you think that? What's your evidence?"), and challenging or providing counterexamples ("Does it always work that way?"). This language appears frequently in the dialogue of expert teachers (see Lampert & Graziani, 2009; C. Lee, 2007; Minstrell & Kraus, 2005; Sohmer et al., 2009).

The work helping teachers learn to use such talk productively has had mixed results. In a quasi-experimental study, Penuel, Moorthy, DeBarger, Beauvineau, and Allison (2012) compared a group of earth science teachers who learned to use tools to orchestrate productive talk (discussed in the preceding paragraph) in classrooms with a similar group of teachers who used the same curriculum but had no access to the tools. The experimental group outperformed the comparison groups' students in two different units of instruction. Qualitative observations of classrooms in the treatment group showed that the classroom had a slower pace, students were asked to imagine why answers they did not pick were reasonable, students took longer turns at talking, and students focused on reasons for their responses.

The orchestration of such discourse in some settings, however, can be problematic. In an analysis of affordances and constraints for scientific discussion in high school project-based science, Alozie et al. (2010) found that even with supports for productive discussion, teachers still relied on traditional recitation formats and low-cognitive-demand evaluative questions. Institutional pressures appeared to work against learning when teachers in this study expressed concerns that they needed to cover content quickly in a short time in order to be seen as addressing state standards. In other cases, it can be difficult for students from nondominant groups who do not command middle-class language practices to participate in or be understood in the restricted space of school discourse (Calabrese Barton & Tan, 2009; Warren et al., 2001). In some instances, students are made to feel their everyday experiences and theories are of no value. In a study of how learners participate in discussions about climate change, Moje et al. (2004) found that urban youth they followed in and out of school settings rarely volunteered everyday knowledge in science classrooms, even when their prior experiences were relevant to the topic at hand. These students worked to navigate between different cultures and different "rules of engagement" in the contexts of school, family, and peers, often with little assistance from teachers. When teachers make clear that different types of knowledge and experiences are welcome in the science classroom, they construct a discursive space that helps students navigate both the everyday world and the world of school (B. Brown & Ryoo, 2008).

Inquiry as an undertheorized representation of science. Up to this point, we have written about "supporting ongoing changes in student thinking" in terms of modeling, investigation, and revising explanations. But science educators may be more familiar with advancing student learning through the process of inquiry. For the past 40 years, inquiry has been portrayed as the quintessential experience for science learners. The previous *National Science Education Standards* (National Research Council [NRC], 1996) featured inquiry both as a special disciplinary pursuit and a pedagogical approach that includes posing questions, designing studies, and proposing explanations based on evidence. But in classrooms during this time, nearly everything that was not direct instruction (including library research, using equipment, group work, etc.) flew under the banner of inquiry (see analyses and critiques by Blanchard et al., 2010; Luft et al., 2011; Minner, Levy, & Century, 2010; Spillane, Reiser, & Reimer, 2002). Inquiry does not have the characteristics of a practice, but rather is a loosely defined approach to knowledge building that makes its value for learning difficult to assess. Inquiry is often reduced to process skills, which are not used to build theory but to confirm known facts. In other cases, inquiry is enacted through "the scientific method." This formula has been critiqued as conceptually narrow (Rudolph, 2005), as a "folk theory" about disciplinary activity that constrains how teachers plan for instruction (Windschitl, 2004), and as demonstrably inhibiting the intellectual work of students (Tang, Coffey, Elby, & Levin, 2010. The scientists who have refuted the notion of a scientific method are too numerous to name them all here. References to the scientific method now appear less frequently in scholarly work as a serious representation of disciplinary practice, yet this caricature of science remains firmly entrenched in school culture worldwide. Our view is that the education community has not yet been able to fashion an alternative image of investigative science that is both comprehensible and intellectually honest and that translates into meaningful classroom activity.

For these reasons and others, the National Research Council's *Framework* document for the Next Generation Science Standards (NRC, 2012) has reduced the references to inquiry and instead refers to science practices. This new conceptualization of disciplinary work is viewed as an advance: "It minimizes the tendency to reduce science to a single set of procedures, such as identifying and controlling variables, classifying entities, and identifying sources of error. This tendency overemphasizes experimental investigation at the expense of other practices, such as modeling, critique, and communication" (p. 3-2). This view of science as practice also corrects the tendency for inquiry to be experienced in isolation from science content. All too often, skills such as hypothesis testing or data analysis, for example, become the aim of instruction rather than a way to develop a deeper understanding of the concepts and epistemology of science.

Despite the ambiguities associated with inquiry, there is a history of engaging students in active investigations that deserves review. Studies that compare an inquiry approach with more traditional types of instruction report similar outcomes—modest but statistically significant differences favoring the inquiry condition (Blanchard et al., 2010; Fogleman, McNeill, Krajcik, 2011; Furtak, Seidel, Iverson, & Briggs, 2012; Kahle, Meece, & Scantlebury, 2000; Lynch, Kuipers, Pyke, & Szeze, 2005; Marx et al., 2004; C. Wilson, Taylor, Kowalski, & Carlson, 2010). At the systems level, gains in student learning through inquiry are more likely to occur when the efforts of teachers, district coaches, and administrators are coordinated around teaching in nontraditional ways, when teachers receive extensive professional development, and when classroom engagement in inquiry lasts for a prolonged period. In one such study, Marx et al. (2004) worked with middle school teachers, students, and district personnel in an inner-city environment in Detroit, Michigan. This three-year program engaged approximately 8,000 students in inquiry-based and technology-infused curriculum units that were collaboratively developed by district personnel and staff. Results showed statistically significant gains on students' posttests, and the strengths of the effects grew over the three years of the study. At the level of instruction during inquiry, scaffolding appears crucial. In a recent meta-analysis of 37 experimental and quasi-experimental studies that contrasted different levels of support for inquiry, Furtak et al. found that conditions in which teachers provided various types of guidance had a large positive effect size compared with unguided forms of inquiry or with traditional (noninquiry) teaching conditions. Other studies have shown no significant differences or have had inconclusive findings (Lederman, Lederman, Wickman, & Lager-Nyqvist, 2007; Pine et al., 2006). In a number of these studies, however, the inquiry experience lasted only a matter of days, or there were limited supports for students in doing the work.

The clearest finding common to all the recent meta-analyses is that, despite crisp definitions of inquiry offered in documents such as the former *National Science Education Standards* (NRC, 1996), inquiry is enacted in classrooms quite inconsistently. In different investigations mentioned earlier in this section, inquiry was taken to mean using curriculum kits, doing projects, doing hands-on work of various types, or having students engage in material activity rather than having the teacher do demonstrations. In the United Kingdom, the concept of "practical work" encompasses a similar swath of instructional arrangements—experiments, investigations, lab work, and so on (see Abrahams & Reiss, 2012). A review of inquiry in science education by Minner et al. (2010) concludes, "It is precisely the lack of a shared understanding of the defining features of various instructional approaches that has hindered significant advancement in the research community on determining the effects of distinct pedagogical practices" (p. 476). The NRC (2012) notes that "[s]uch ambiguity results in widely divergent pedagogic objectives—an outcome that is counterproductive to the goal of common standards" (p. 3-2). Without a clear vision of authentic practice, no cumulative knowledge base will develop on effective teaching or on learning environments in general. Even what is measured as outcomes will be unclear. Most problematic of all, the lack of a common vision works against the continual improvement of teaching—by individuals and by the field.[4]

Summary. The work of science teaching is increasingly being conceptualized as supporting ongoing changes in student thinking about challenging questions or puzzling situations associated with natural phenomena. These changes can take place in the context of scientific practices that draw upon interrelated conceptual, social, epistemic, and material activities. The science practices can be thought of as an ensemble of strategies that work together to build understanding. Of these, modeling appears to be unique in that it can serve as a superordinate activity, organizing and motivating engagement in other practices that, in total, support the iterative refinement of science ideas by learners.

The images of instruction aligning with such practices are unfamiliar to many educators; there are few reports of teachers engaging in this type of work unless they have had extensive professional development with ambitious forms

[4]Confusing the public discourse further are highly visible studies that have attempted to characterize inquiry or discovery as "minimally guided" forms of instruction (a view not shared by the field) and have compared largely unstructured learning conditions to those of direct instruction (Klahr & Nigam, 2004). Still others (Kirschner, Sweller, & Clark, 2006) tend to lump inquiry, discovery learning, problem-based learning, and experiential learning approaches together, suggesting that all of these methods are "pedagogically equivalent approaches [that] include science instruction in which students are placed in inquiry learning contexts and asked to *discover* the fundamental and well-known principles of science by modeling the investigatory activities of researchers" (pp. 75–76).

These studies have been critiqued primarily for two assumptions built into the work—that the larger research community maintains a type of inductivist stance toward science instruction, and that the dominant designs for student inquiry advocate for little or no guidance from the teacher. Regarding the first, the inductivist view holds that all knowledge—even theoretical concepts—emerges directly from facts and observation. It has asserted itself in naïve "discovery methods" adopted by some curricula in the United Kingdom and the United States. Refuting such a stance, Driver (1994) cautioned, "More is required than simply providing practical experiences; the theoretical models and scientific conventions will not be 'discovered' by children through their practical work. They need to be presented" (p. 47). In other words, young learners can identify patterns, trends, and inconsistencies in data, they can even invent ways to conceptualize processes and events, but they cannot use observations to spontaneously generate theoretical, unobservable entities, events, or processes. Ideas such as recessive alleles, chemical equilibrium, or tectonic plates have to be introduced by teachers at appropriate moments, and then used by students as tools to reason about the theory and about the world around them.

Regarding the second assumption, Bybee et al. (2006) and Hmelo-Silver, Duncan and Chinn (2007) describe how the research community's conception of inquiry is far from being "minimally guided," relying in fact on significant and strategic scaffolding to guide student learning, and it commonly involves timely direct instruction (Blanchard et al., 2010; Bybee et al. 2006.; Schwartz & Bransford, 1998).

The point here is not that fields of research have their controversies, but rather that the already messy business of studying science teaching can be made nearly impossible by the ambiguous language applied as shorthand to the conditions of instruction under scrutiny. *Discovery* and *inquiry* as descriptors for a course of activity for young learners have lost much of their linguistic value in the marketplace of ideas about instruction. Even more problematic, studies making sweeping claims about discovery or inquiry find their way into the headlines of practitioner literature, without the assumptions underlying the studies being made clear or an acknowledgment of the complexity of human learning.

of pedagogy. Orchestrating this activity calls for a diverse toolkit of talk moves and strategies for continually working on productive social norms in the classroom. Talk, however, is not all that should attract researchers' attention. Students bring a whole range of resources to the classroom. More work is needed on how teachers can recognize and capitalize on these resources, such as students' partial understandings, their everyday language, and their everyday experiences. Strong anecdotal evidence suggests that some teachers are predisposed to attend to students' reasoning and to use students' ideas productively in instruction. Other teachers appear unable to recognize or cultivate students' reasoning—the latter rendering many professional development efforts ineffective. Is responsiveness, which is crucial to ambitious teaching, "instructable" in teacher training or professional development? Some studies suggest that teachers can shift their practice in this direction or enhance what they already do, but the specific means of support that help them recognize students' thinking and use it as a resource to shape learning for everyone in the class remain unclear.

Example of a set of core practices around supporting ongoing changes in student thinking. The research described earlier in this section encompasses three broad types of teacher interaction with students, each of which might constitute a core practice: (1) introducing ideas to reason with; (2) engaging students with data; and (3) using knowledge products to revise theories or models (see Table 18.3). The first of these involves a "time for telling" in which the teacher selects some idea associated with the anchoring phenomenon that is not "discoverable." Rather, it must be introduced to students with the intention of having them use it in the subsequent practice as a lever for reasoning about observations and patterns in data. The introduction of conceptual ideas can be determined by students' current gaps in understanding or by a teacher's inference of what a logical next step is in constructing an explanation for the anchoring event. (We acknowledge here that there is no research consensus about whether teachers should introduce new conceptual ideas as a prelude to investigations, labs, or activity, or alternatively, whether they should engage students in activity before introducing new ideas. And this dichotomy, of course, oversimplifies the choices teachers have in interrelating "instructed ideas" with various forms of students' sense-making activities.) The second practice involves scientific work, such as hypothesizing, carrying out studies, and making sense of data patterns and new ideas. The third involves returning to public records of thinking and making revisions based on new data and new concepts introduced during instruction. This set of practices would be used *multiple times* throughout a unit as students gradually work toward more coherent, elaborated, and accurate scientific understandings of complex phenomena.

In the case represented by Figures 18.6 and 18.7, a high school physics class was studying the relationships among force, motion, inertia, and friction. The anchoring event to be explained was an example of urban gymnastics, in which a young man ran up to a wall, planted his foot on the wall, did a back flip, and landed on his feet. Midway through the unit, after students had done several lab activities, they were asked to comment on their peers' models. For English Language Learners and other students, talk and activity around the drawing of scientific models often moves too quickly for them to participate. In this case, the teacher set aside time in class when everyone received sticky notes and wrote comments to affix to someone else's model. A comment could be a suggestion to add an idea, revise something, or remove something. Or a comment could be a question. In this way, students learned to give and receive opinions about the quality of science ideas. Students were scaffolded in the work by the tool illustrated in Figure 18.7. These sentence frames helped students understand "what counts" as a productive comment, meaning one that links activity and new ideas with changes in claims or in models. Because these students were so unsure about how to comment on the thinking of others, the teacher first had them use each type of prompt (add, revise, remove, and question) to comment on their own models.

There are many possible representations of this work, but we have crafted this particular example (Figure 18.7) by using principles with an evidence base in the literatures cited in this section. We note that not all the principles we have articulated can be explicitly embodied in this concise description of practice.

Translating Scholarship to Practices: Supporting Students' Evidence-Based Explanations

Explanation and argument are scientific practices that represent benchmarks of knowledge building in a community. In the classroom, these rhetorical structures coordinate the conceptual, social, and epistemic resources of the collective to explore the questions, What do we *now* know? Why do we believe it? We first unpack the idea of explanation by pointing out the often-confusing overlaps between the colloquial and the scientific uses of the term. Without attention to these varied meanings, studies of how teachers support explanations might be observing and promoting very different types of practices.

There is considerable ambiguity in the research literature and in classroom practice regarding the various meanings of *explanation*. This may be due to the ways the word *explain* makes its way from everyday conversation into the classroom. In the science education literature, it is

TABLE 18.3. Supporting Ongoing Changes in Student Thinking

Goals:

One goal is to engage students in scientific practices as appropriate—posing questions, designing ways to collect data, collecting and analyzing data, or evaluating a model for gaps or inconsistencies—for the purpose of better understanding a process or event that has both observable and nonobservable features. A second goal is to foster productive talk between students in the form of developing ideas and critiquing one another's thinking. A third goal is to support student metacognition in the context of revising a theory or model based on new observations and ideas.

Principles:

- To work on students' ideas, thinking must be made visible and public.
- Learners cannot "discover" theoretical entities or processes; these must be introduced at strategic times by the teacher and used as tools to reason about phenomena, rather than be merely confirmed in activity.
- Students can learn to participate in science if the epistemic "rules of the game" are made explicit and modeled by others.
- Scientific practice best supports learning when treated as an ensemble of activities that derive meaning from one another.
- Knowledge production in the classroom and in science is supported when theories and models are revised over time to become more consistent with evidence and more internally coherent.
- Tools and scaffolding are necessary to do the intellectual and social work of science.
- Material activity by itself is weakly linked with learning. Sense-making talk during and after an activity and opportunities for metacognition are more strongly linked with learning.

Prototypical sequence of tasks and talk:

Practice1 Introducing ideas to reason with

1a. Identifying a new idea that will move thinking forward. Students are asked to consider their current model/theory and to determine what information they need to move their understanding forward. Alternatively, the teacher introduces some component idea of the anchoring phenomenon.

1b. Exploration through activity. The teacher provides a brief probing experience with materials, media, or "what-if" scenarios in order to prompt thinking and questions about the new idea, but also to listen for how students are relating these experiences to what they already know.

1c. Time for telling. The teacher decides if direct instruction is needed to explicate an idea that is not "discoverable" via material activity. If direct instruction is presented, the teacher prompts students to use this idea as a conceptual tool in a new round of activity.

Practice 2 Engaging with data

2a. Reengaging with activity. The teacher may engage students in designing a study, collecting data, and analyzing data, allowing students to make decisions about these practices. Alternatively, students could engage with secondhand data or a teacher-led demonstration to generate observations.

2b. Thinking about patterns in observations. As students engage in conducting some experiment, observation, or other activity aimed at developing a concept, the teacher probes their thinking in small groups. "What patterns do you see?" "What do you think is causing these patterns?" "How are these patterns related to the new concept, process, or event?" The class then come together to discuss what trends and patterns they noticed, and how these relate to the new idea.

Practice 3 Using knowledge products to revise theories or models

The whole class then returns to a public representation of its theory or model and engages with these questions: "With what we now know, how would we change our models or explanations?" "Do our data and new conceptual understanding convince us that our models should change?"

At this point, there should be opportunities for students to hear how their peers are thinking, to respond, and to have this form of disciplinary rhetoric modeled by the teacher. Tools here might include a set of sentence frames for how one makes a statement about new evidence or a public summary table that keeps track of the various ideas and activities explored up to this point.

common to see *explanation* used as to mean "clarification of a term" or "laying out one's reasoning about a problem." For example, in science classrooms, students are frequently asked to explain their reasoning while solving a problem ("Can you explain how you calculated the amount of force needed to lift that load with the pulley system?"). Or they might be asked to explain the meaning of a technical phrase or perhaps explain the results of an experiment. Providing such explanations—or, more properly, *explications*—is in many ways an authentic communicative practice in the daily work of scientists, who clarify ideas and findings for each other and for various audiences (Knorr-Cetina, 1999; Latour & Woolgar, 1979), but these products of intellectual work are qualitatively different from a scientific explanation.

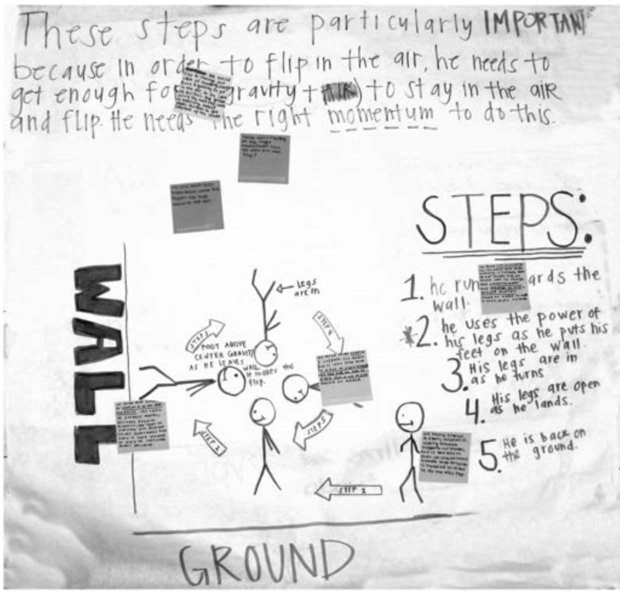

Figure 18.6. Explanatory model created by high school physics students describing why a person could do a back flip by running up to a wall and pushing off. Notes affixed to models are comments from peers as to how model might be adjusted based on evidence. Note on lower left reads,"We think according to Station 4 with the different surfaces, the type of surface matters because friction matters. The type of surface you kick off of (wall) determines how hard or easy it is to overcome static friction."

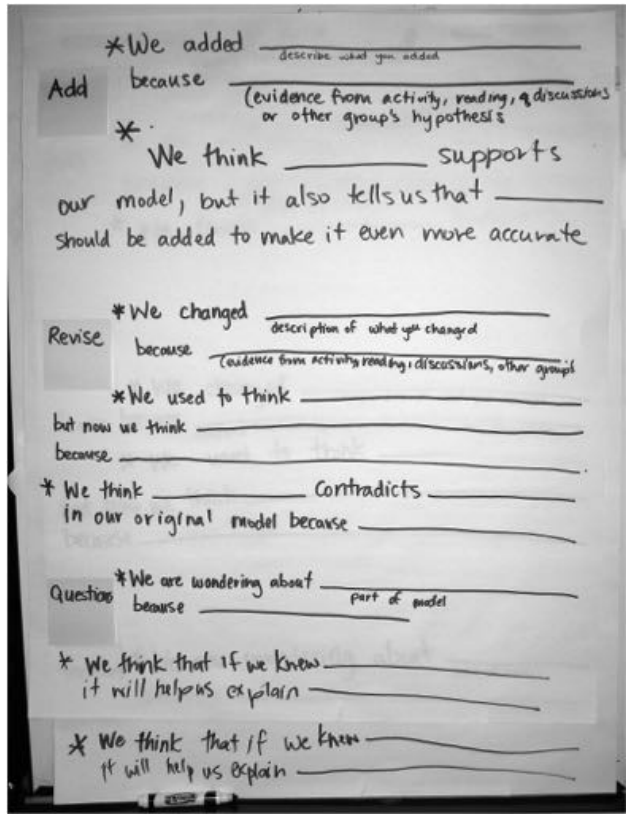

Figure 18.7. Sentence frames that allow students to engage in epistemic talk about how and why models might change in response to evidence. Sentences are written on note cards and affixed to models in relevant places.

The practice of constructing scientific explanations that account for natural phenomena involves more than explications of meaning (Braaten & Windschitl, 2011). For these purposes, causal and statistical explanations are used frequently in formal science. *Causal* explanations are observation of patterns in data, and explicitly seek underlying reasons for these (see Salmon, 1989). By "underlying," we refer to entities, processes, and properties that are not directly observable. In school settings, causal accounts use underlying mechanistic properties, processes, and so on, to explain observable phenomena (Driver et al., 1996; Hammer, Russ, Mikeska, & Scherr, 2008; Perkins & Grotzer, 2005). Assembling these explanations can make students more aware of scientific epistemology, specifically, the conjectural relationship between observation and theory.

The mechanistic view may not always be appropriate in elementary school settings where "causes" for events may well be visible and concrete (e.g., sources of pollution in a local stream). Even without invoking unseen influences or using conceptual language, young learners can collect data, evaluate evidence, and argue for coherent explanations. These exceptions notwithstanding, for the purposes of school science, causal explanations can be conceptually rich and support challenging epistemic conversations about data (the observable) and theory (the unobservable).

Not all branches of science, however, seek mechanistic causal explanations. Fields such as computational biology or quantum physics use statistical and probabilistic reasoning to make sense of phenomena for which there may be no definable cause or regular mechanism (Knorr-Cetina, 1999; Nersessian, 2005; Pickering, 1995). Other fields, such as classical physics, employ laws (statements of observed regularities, often codified in equations) rather than underlying causes to account for the operation of simple machines or to describe the motion of objects. Both statistical and causal explanations require that teachers press for reasoning that goes beyond description, but studies of science teaching rarely clarify what *explanation* means or contrast their use of the term with other possible meanings. This of course makes it difficult to look across studies to make judgments about effective scaffolding or supportive discourse.

Causal or statistical explanations of authentic (rather than generic) events require time, tools, and opportunities to think with others. In nearly all studies where researchers had a hand in designing explanation-oriented activities, the phenomenon being explained required a succession of observations or experiments, the coordination of multiple science concepts, and repeated opportunities by students to reason about these resources in order to refine their explanations or models. This *drawing together* of learning experiences that have occurred over time is not common in schools; students are most often asked to explain the results of a single experiment (which typically is a restatement of data trends) and then move on, rather than using experimental results together with other observations and ideas to revise their thinking about a phenomenon of richness and complexity (Banilower, Boyd, Pasley, & Weiss, 2006; Bowes & Banilower, 2004; K. Roth & Garnier, 2007).

A related science practice, argument, incorporates explanation with evidence and reasoning. Here, the goals are for the student to articulate his or her understandings and work to persuade others in order to collectively make sense of the phenomenon under study. The literatures on supporting explanations and arguments have in some cases overlapped, but not without some controversy about whether they should be treated in classroom practice as distinct forms of rhetoric (see Berland & McNeill, 2012; Osborne & Patterson, 2012). Engaging students in argumentative discourse is difficult for a number of reasons. When confronted with data sets, students struggle to select appropriate observations to use as evidence (McNeill & Krajcik, 2008) or provide sufficient evidence in written explanations (Sandoval & Millwood, 2005). Even when students can use evidence to make sense of phenomena and articulate those understandings, they do not consistently attend to the goal of persuading others of their understandings (Berland & Reiser, 2009). Moreover, students find it difficult to provide reasoning for why they chose particular forms of evidence (Bell & Linn, 2000; McNeill, Lizotte, Krajcik, & Marx, 2006).

Combining explanation and scientific argumentation is complex and requires a learning environment designed to elicit student participation, with norms in place for criticizing ideas and for ways of talking, and with tools relevant to the difficult aspects of this work. But when traditional school routines encourage students to articulate explanations, there is rarely the expectation that these will be challenged or judged against other explanations (Driver, Newton, & Osborne, 2000; Lemke, 1990). Persuasion requires social interactions that are often inhibited by traditional classroom interactions (the emphasis on "correct" answers and the norm of one- or two-word utterances by students). Because argument, or simply talk about evidence, is not common, teachers themselves have had few opportunities to use these specialized forms of rhetoric as learners (Zembal-Saul, 2009). Sampson and Blanchard (2012) found, for example, that secondary science teachers were not adept at using data to support reasoning about explanations of natural events. Some of the teachers (most of whom had undergraduate degrees in science) reported never having participated as learners in a class where explanations were evaluated.

McNeill and Krajcik (2009) recommend that students be provided with both general support for the argumentation framework of "claim, evidence, and reasoning," as well as context-specific support for what counts as each of these components of a particular scientific domain. These complementary supports are intended to reduce the complexity of the instructional context by defining an otherwise ambiguous and unfamiliar problem space, which can then enable students to have greater success with the practice of argumentation. Zembal-Saul (2009) has reported that providing such frameworks to elementary teachers helps them not only stimulate talk about evidence with young learners, but also helps them attend to student thinking. We note, however, that in the areas of explanation and argument, there is a need for more studies that examine the role of domain-general heuristics for students (and for teachers when they receive professional development) while taking into account the domain-specific forms of argument that characterize authentic science, as well as the role of domain-specific conceptual knowledge (Osborne, Simon, Christodoulou, Howell-Richardson, & Richardson, 2013; Perkins & Salomon, 1989). There is more general agreement that teachers should develop simpler initial instructional contexts for students to engage in argument, with supports that make the expectations for participation explicit. Within these situations, teachers can help students understand what counts as appropriate and sufficient evidence for a particular scientific claim.

Thus *framing* the activity once again becomes important. Ford and Wargo (2012) draw upon the interactionist literature to suggest that teachers should lay out for students "what is being done with knowledge" in a particular classroom routine. Over the past three decades, this practice of teachers making clear, in talk and in practice, what everyone's role is in the production of knowledge, and whose knowledge will be valued, shows up consistently in classrooms where widespread student participation and learning are evident (see A. L. Brown & Campione, 1994; Engle, 2006; Magnusson & Palincsar, 2005; Rosebery et al., 2010).

In classrooms where explanation and argument are well supported over time, one can see how this intellectual work is intimately related to other scientific practices, and how conceptual, social, epistemic, and material dimensions of the practices can be skillfully coordinated to support the advancement of understanding. A case in point for incorporating these ideas into the design of instruction comes from Radinsky et al. (2010), who describe a middle school classroom in which students were developing models for the movement of the earth, sun, and moon. The teacher and students began coconstructing an initial explanation by reviewing the community's shared assumptions about the relevant science ideas. Students then engaged in successive inquiries. They referenced peers' ideas and experimental results as warrants for changing their explanations, building from isolated ideas—attributed to specific individuals—toward a coherent whole-class model, which was attributed to the community. The study identified the means by which proposed explanations were taken up and developed by the class, including using multiple shared representations, leveraging peers' language to clarify ideas, and negotiating the language and representations for new, shared explanations.

Summary. As with so much of science education research, the vast majority of empirical research focuses on what students are able to do. The parallel literature about the knowledge, resources, and judgment that teachers deploy in supporting explanation and argument is remarkably thin. Forms of support for students' explanation and argument are largely inferred from studies of students and how they respond to special interventions that researchers introduce in the classroom. From a practice-based perspective, there is a gap in the literature about how teachers engage in explanation and argument, and how supports for teachers might be developed.

Also unresolved in this literature is how teachers can walk the fine line between having students synthesize well-supported explanations and having them simply reproduce textbook accounts. The reproduction of a canonical explanation requires little more than memorization, aided in some cases by modest levels of comprehension. This illustrates yet another reason why units of instruction might be best grounded in complex but accessible phenomena rather than well-structured problems lifted from the pages of a textbook. In studying force and motion, for example, the fully elaborated explanation for why karate champions can break boards in some cases but not others has a number of interconnected conceptual threads (the acceleration of the hand, equal and opposite reactions, the "give" of the board, the force per unit area, the conservation of energy, etc.), which must be interwoven to create a coherent account of martial arts success or failure. Such explanations might be rich precisely because they come from familiar, everyday contexts, with attendant details that require more links among ideas than back-of-the-chapter problems do. For the teacher, then, there is a balance between supporting the construction of explanations that may take a variety of legitimate forms and ensuring that scientifically rigorous ideas and language are integrated into students' explanations. There are case studies of teachers navigating this territory (Grotzer & Basca, 2003; Magnusson & Palincsar, 2005; Stewart, Cartier, & Passmore, 2005), but there have been few systematic syntheses of what professional reasoning and practices are involved. This form of expertise remains elusive, in that it is difficult to define, to represent, or to support in other professionals.

Example of a set of core practices around supporting students' evidence-based explanations. The candidate core practices that follow (see Table 18.4) describe a sequence of events that might take place near the end of a unit of instruction. We recognize that specific moves in these practices, such as questioning students about gaps in their models or asking them to talk about evidence, would take place throughout a unit of instruction. This design presupposes that students are developing an evidence-based explanation for a puzzling situation that requires an understanding of multiple science ideas; it also assumes that students have used public documents to keep track of successive activities during the unit, which have contributed to their thinking about the phenomenon they are explaining.

In the case illustrated by Figures 18.8 and 18.9, a middle school teacher was completing a chemistry unit on phase change and preparing students to draft a final evidence-based explanation, which would be presented as a pictorial model accompanied by text. In this unit the students were attempting to explain how a soft drink could be "distilled" into pure water. The explanation required students to interrelate ideas, such as the conservation of matter, the relationship between heat and phase of matter, intermolecular bonds, and the chemical properties of matter. Throughout the unit, the teacher and students had used a tool called a summary table (Figure 18.8). Each row of this table was filled in, using students' language, after an activity. The rows included drawings of the activity, observations students had made during the activity, and a description of how that activity had helped students understand the focal questions of the unit. The summary table organized what otherwise might have been perceived as separate and isolated lab activities. It was used during conversations with students about how to bring in multiple forms of evidence to support a final explanatory model. The tool shown in Figure 18.9 helped students use evidence from one of several activities to support a particular part of the overall explanation for the distillation phenomenon. One such card reads "The Starbucks cup activity explains part of the Coke lab because it tells us that the molecules on the outside (air, gas) molecules can attract to other molecules, making water."

Implications and Recommendations for the Advancement of Teaching

We have taken an unconventional approach in writing this chapter, using the literature to build a case for prioritizing particular forms of teaching practice and, in the process,

TABLE 18.4. Supporting students' evidence-based explanations

Goal:

To support students in looking across the various ideas and data explored in a unit in order to construct a final, evidence-based explanation for the anchoring phenomenon.

Principles:

- Causal explanations in science draw upon multiple forms of evidence and multiple ideas.
- This coordination requires specialized tools for organizing ideas.
- Students benefit when the teacher is explicit about what counts as evidence, how it is used to support explanations, and in general what the rules of epistemic talk are in the classroom.
- Explanations for *contextualized* events or processes can take many legitimate forms and can be expressed in different ways. This heterogeneity in student expression stimulates comparative reasoning about the understanding of scientific concepts and explanatory coherence.
- Reproducing canonical explanations can result in fragile, short-lived understandings.

Prototypical sequence of tasks and talk:

Practice 1 Prompting reasoning about gaps and contradictions in explanatory models

1a. Updating explanatory models. The teacher asks students in small groups to update the most recent iteration of their models. Students attempt to incorporate the relevant ideas and forms of evidence they have encountered during the unit. Even though the teacher and students have been revising explanatory models or representations of theories throughout the unit, a complete explanation would be difficult without special scaffolding and tools. Scaffolding moves might include guides for what to include in an explanation (such as the use of specific science language, reminders to describe what is not observable, leaving designated space for students to write and to draw a pictorial or schematic model, or dividing a phenomenon and its explanation into "before, during, and after"). Special tools might include student-created explanation checklists or a table that summarizes ideas and different types of evidence assembled across the unit (described in Table 18.3).

1b. Questioning students about the coherence of their models. As small groups of students update these explanatory models, the teacher circulates throughout the room with questions that prompt students to consider gaps or contradictions in their final explanations—"You seem to have a beginning and an end in your explanation, but what is happening in the middle?" "This part of your model looks like it may not 'fit' with other parts."

Practice 2 Supporting evidence-based argument

2a. Preparing to persuade with evidence. As the updated models are nearing completion, the teacher asks students to be prepared to defend one key aspect of their explanatory model by using relevant evidence from a public record, such as a summary table (a tool students use to organize the major ideas and observations during the unit, including how these might contribute to understanding the anchoring phenomenon of the unit).

2b. Public comparisons of evidence-based explanations. In the latter half of this practice, perhaps the following day, teachers would reassemble the class and have groups of students compare explanations with one another. These groups could defend one particular part of the explanation to the class, cite the evidence used, and discuss the reasoning they used to link the evidence with the claim (another instance in which sentence frames or other language support is effective). The teacher could select groups who have contrasting explanations to present publicly and ask the entire class to comment on the use of evidence and explanatory coherence. Questions here might be "What evidence appears to be convincing, and why?" and "What gaps do we still have in our models and explanations?"

2c. Making adaptations. The teacher asks student groups to return to their explanations, make adjustments, and consider what unresolved puzzles they still have. This practice does not represent a final assessment; teachers would use this activity to find out what critical inconsistencies remained in their students' understanding and address these before holding students accountable for an evaluation activity.

proposing key parts of a system of professional activity that can improve instruction over time. Our logic can be summarized this way: Knowledge for and about science instruction is a type of professional capital that has never readily accumulated in schools. This works against the common goal that practitioners and researchers share—the continual improvement of teaching. There are many reasons for this situation, some of them related to how schools are organized (or not) for professional learning, some related to teacher turnover, others related to teacher preparation, and still others related to the general lack of consensus about the goals of science education. But more fundamentally, at every level of analysis, there is a lack of grammar about practice itself. This is evident in public conversations about reform, in theories of educational leadership, in schools themselves, and in the research community. This is problematic because the way teachers interact with students regarding subject matter is what most directly mediates learning—and because the particulars of these interactions matter.

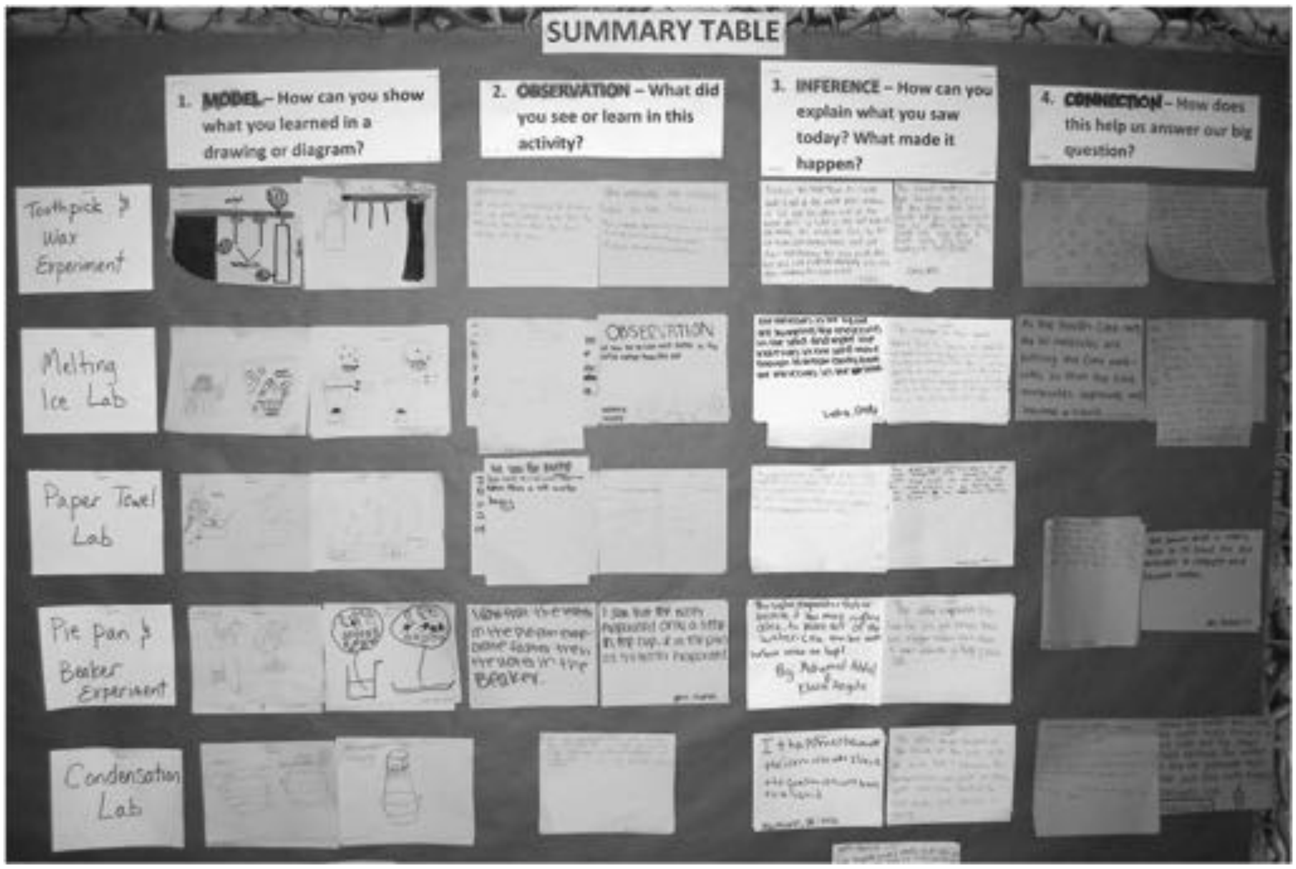

Figure 18.8. Summary table tool that organizes all activity and readings, and how they each relate to building a final explanatory model. Students fill in each row after an activity; these are then used as evidence to support or refute parts of their models. This tool used by sixth-graders to explain the roles of heat, molecular motion, intermolecular forces, and phase change in explaining what happened when they "distilled"a soft drink.

***Recommendation:* Develop a clearly articulated vision of instructional excellence that is (1) informed by students' wide-ranging abilities to engage in science, and is (2) defined in terms of core teaching practices that are learnable by individuals and improvable by the practitioner and research communities.**

Without some common frameworks to describe and guide good teaching as practice, it is difficult for either researchers or practitioners to communicate about meaningful classroom problems. And it is especially difficult for professional knowledge to be shared, tested, and refined over time. In our current system, the work of science teaching is characterized by individualism and institutional isolation (Little, 1990; Lortie, 1975; Tyack & Cuban, 1995). Thus the ceiling for a teacher's improvement over a career is low, constrained primarily by his or her personal experience. We propose that the floor be raised, using a reliable, evidence-based, teachable, and learnable set of practices for beginners, together with the tools that can support such practices. From this elevated platform the ceiling could be raised, maintaining the trajectories of experienced teachers who engage in continual principled experimentation in classrooms while using increasingly sophisticated versions of these practices and tools.

The conversation about teaching as practice cannot begin, however, without articulating a vision of instruction that is very different from what can be observed in many classrooms today. And so we have taken up the idea of ambitious teaching as a way to express this vision. The images of rigorous and equitable teaching come to life through close attention to practice, so scholars must identify moves that are linked in the literature to increased student participation and learning. Of these practices, two questions may be asked: (1) Are some of these more important than others in terms of supporting student learning? (2) If so, what should constitute a core of practices to which communities of practitioners could devote their resources?

These "core practices" could support the continual improvement of teaching in a number of ways. They would not only have evidentiary warrants in the literature linking them to student learning, but they would be definable and recognizable to others striving to improve their practice. This collective familiarity could then support a shared

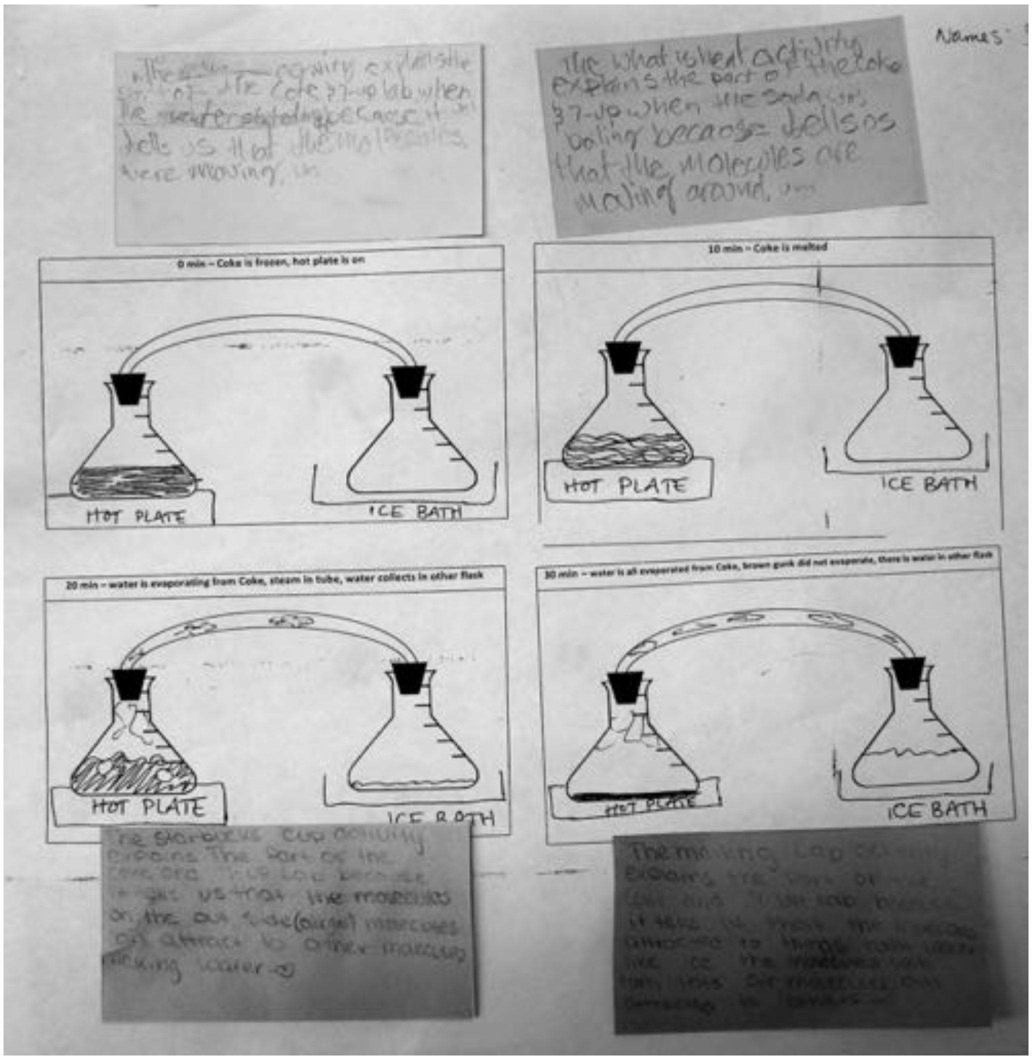

Figure 18.9. Supports for final explanatory model depicting how a soft drink could "distill" into pure water. Handwritten notes describe how an activity done during the unit provides evidence for one part of the overall explanation. The note in lower left reads "The Starbuck's cup activity explains part of the Coke lab because it tells us that the molecules on the outside (air, gas) molecules can attract to other molecules, making water!"

language among teachers about instructional goals, tasks, talk, and tools. As a teacher learns to articulate the reasoning behind his or her professional decisions to others, this communication deprivatizes teaching and sets the stage for innovations in which variants of these practices are tried out and evidence of student learning and participation are collected. Principled experimentation prompts the development of tools to support special forms of intellectual work by students, and these tools in turn shape the practices in potentially productive ways. For these reasons, we view ambitious teaching and core practices as a research and development effort, shared between the research community and the practitioner community, to improve science teach*ing* as well as to support science teach*ers*.

Out of this nascent work a *new and different image of expertise* is already emerging. Teachers deploy specialized knowledge of subject matter to make curricula more rigorous and at the same time more accessible to learners, scaffolding students for fuller participation in science practices, developing tools for all students to do intellectual work, using a broad repertoire of discourse moves to stimulate deep thinking, supporting metacognition, and of course developing these capacities further by reasoning about and learning from their practice in collaboration with other educators. This "new expertise" is defined by alignment with research on effective professional practice and by accountability to the full spectrum of young learners in the classroom. This view of accomplished teaching is responsive to students' ideas, experiences, and needs, and relies less on a teacher's polished and predictable routines, stagecraft, or expositions of his or her own subject matter knowledge.

Recommendation: **Develop more coherent and useful theories of student engagement.**

The knowledge base we will depend upon for the transformation of teaching is currently a patchwork of partial understandings. One of these partial understandings is how teachers learn to *engage* students over extended periods of instruction. From the curricular perspective we know that situating science ideas in everyday phenomena generates student interest, but a great deal of important science content is difficult to place in familiar contexts. Conversely, there are accounts of teachers crafting units around puzzling questions that have little to do with students' lived experiences, yet the questions intrigue and motivate young learners. The *accessibility* of science ideas to students is another likely criterion for engagement, but we are not sure if accessibility is a quality of the science content, of how it is represented to students, or of how learners are asked to reason about it. Sustained interest and engagement in science classrooms may be driven as much by students' anticipation of regular and purposeful social interaction as it is by the selected content or the appeal of "hands-on" activity (see Ferguson & Ramsdell, 2012). Yet another feature prompting engagement in the classrooms of highly responsive educators is when students' ideas—initial theories, everyday experiences, or ways of describing phenomena—are treated as legitimate resources for use by the rest of the class. Even when roughly enacted by a teacher, there is abundant evidence that these moves stimulate a sense of agency in students and develop their identities as knowers of science.

We have examples of thoughtful theorizing about how features of instruction influence engagement (Nasir et al., 2006), but more needs to be done to link these strategies and engagement itself with student learning. The endgame here would be the development of design principles for engagement that are accessible to teachers. To do this, researchers need to unpack the relationships among interest, engagement, agency, participation, identity, challenge, and common interactions in the classroom. What we know with certainty is that without student engagement, all attempts at meaningful teaching are compromised. Planning for the intellectual engagement of all students, then, is part of the work of ambitious teaching.

Recommendation: **Study teachers and their evolving practice over longer timescales.**

Other parts of our knowledge landscape, important to the widespread cultivation of ambitious teaching, lack even the most basic empirical foundation. Chief among these is an understanding how science teacher practice develops over time. Longitudinal studies that track what happens in the classrooms of science teachers are nearly nonexistent. Novice–expert studies in science, for example, do not follow beginners over time to see what influences their movement toward effective practice. Rather, one group of novices is compared with a different group of experts, and inferences are made about the kinds of support necessary to put beginners on a pathway to excellence.

The small number of studies that have followed the early practices of teachers (from a few months to about two years) have revealed similar findings that are both puzzling and counterintuitive. Two of these investigations (Kang & Anderson, 2011; Thompson et al., 2013) found that after matriculating from reform-oriented teacher preparation programs, about one third of novices were able to enact thoughtful and effective forms of teaching in the classroom, even in their earliest attempts with students. Almost without exception, these individuals shared three fundamental characteristics. The first was their ability to "unpack" ideas in their curriculum—to understand for themselves which science ideas had the most explanatory power, to imagine the reasoning processes students would go through to understand such ideas, and finally, to construct a sequence of curricular activities to accommodate this reasoning. The second common characteristic emerged during instruction itself. Effective novices in these studies were interested in and responsive to student thinking, often using students' ideas or puzzles as legitimate resources for whole-class development of scientific understanding. They made student thinking public and provided opportunities for everyone in the classroom to build upon that thinking. The third similarity among these beginning teachers was their ability to learn from their peers' experiences and from their own students during instruction. Consequently, these novices started off with more effective teaching, but more important, they continued to learn at a faster pace than their peers. In both studies, the remarkably sophisticated teaching by this subset of individuals was apparently unaffected by pressures in their school contexts to moderate expectations for students and teach in more conservative ways. Other literatures describe how these three characteristics have revealed themselves in teachers during training or professional development. These literatures have also documented similar forms of "generative" change in pedagogy (see, e.g., Franke, Carpenter, Levi, & Fennema, 2001). Teachers must find ways to hold their pedagogical ground in the early years of their career because, as Luft et al. (2011) report, beginning science teachers without science-specific induction support tend to regress away from reform-oriented beliefs and practices as they work in schools and as they take on added professional responsibilities between their first and second year.

These studies leave us with questions. Why do these characteristics "cluster" together in the same individuals in ways that make even their first attempts at teaching, although clumsy in implementation, seem expert in intent?

How do these early-career educators resist conforming to traditional ways of teaching when encountering challenging school contexts? Can these abilities be systematically cultivated in other novices? If so, how?

Recommendation: **Develop ways to characterize and support the work of those who teach teachers.**

As the demands of ambitious teaching become better understood, it seems clear that science teacher preparation must be reinvented. Currently, instruction about instruction in many training programs is largely underinformed by the knowledge base on teacher or student learning (Rand, 2002; U.S. Department of Education, 2008). Rather, novices' exposure to pedagogy is limited to the past experiences, skills, and worldviews of their instructors and cooperating teachers (Ball et al., 2009; Deussen, Coskie, Robinson, & Autio, 2007; Little, 1990). Although few specifics are known about the preparation that occurs in methods classes (Clift & Brady, 2005), we do know that typical training for teachers focuses more on managing material activities and students themselves, and less on designing opportunities for students to reason about science (Adams & Krockover, 1997; Freese, 2006; Grossman et al., 2009; Levine, 2006).

One clear policy recommendation supported by this review is to raise the bar for how science teachers are trained and supported across a career. We recommend that those who teach science teachers (e.g., methods instructors) should at least have an established record of being able to engage K–12 learners in some of the ambitious practices described in this review. These are reasonable expectations, especially compared with the expertise required by those who teach architects, surgeons, engineers, or airline pilots. The complexity of ambitious teaching also means that teachers in training should have multiple opportunities in authentic circumstances—extending over months—to approximate these practices and receive productive criticism from well-informed others. Nearly every high-achieving country has taken up such a rigorous regime for science teacher preparation; meanwhile, the United States, whose middling status in international comparisons of science learning has not changed since the mid-20th century, is now lowering preparation standards on a state-by-state basis (Darling-Hammond, 2011).

In terms of professional development, five frequently cited characteristics appear to support teacher learning: (1) focusing on specific content, (2) engaging teachers in active learning, (3) enabling the collective participation of teachers, (4) coherence with school policy and practice, and (5) duration of the professional development (Desimone, 2009; Supovitz & Turner, 2000). These are largely drawn from quantitative studies and do provide some guidance in the design of professional development. Researchers, however, lack a clear theory of the underlying mechanisms involved in science teacher learning (see S. Wilson, 2013). We do not know, for example, how and why particular features of professional development (such as duration) influence or mediate learning, or why professional development designs work well for some but not for others. From the literature presented in this chapter, it seems clear that professional development providers need to help teachers learn to "work on and with" students' ideas. Professional development providers also need to focus on practice itself as the object of study and change over an extended period of time. Neither of these are typical of current professional development.

Without attention to practice—especially the sequences of tasks, talk, and tools—other ways of representing teaching do not appear effective. Even explicit principles for instruction vastly underspecify how teaching should unfold in classrooms. Several research groups that work extensively with teachers recognize that unless educators have opportunities to engage in and learn from practice itself, the principles underlying the instruction, no matter how carefully conceived, do not support decision making very well. Scardamalia and Bereiter (2006), for example, observe that principles—whether framed as goals, rules, beliefs, design parameters, or diagnostic questions—are viewed by some teachers as too abstract to be helpful and by others as descriptions of things they already do. Video and examples from student work can arouse interest in knowledge-building approaches for the classroom, but the result is often a heightened demand for "how-to-do-it recommendations" (see similar notes by A. L. Brown & Campione, 1996; Lehrer & Schauble, 2006). There is evidence, however, that when teachers are engaged in looking at video from their own classrooms, using conceptual frames for talking productively about what they intended to accomplish in their interaction with students (Warren & Rosebery, 2011), or they are asked to analyze the student thinking that is reflected in written work, with the intention of revising instruction, learning that has an impact on subsequent practice can occur (Heller, Daehler, Wong, Shinohara, & Miratrix, 2012; Ruiz-Primo & Furtak, 2007).

There is much research and development to be done here. Perhaps we should borrow, once again, the idea of framing as a way to help clarify the purposes and means of professional development by identifying what roles different actors will play, with what tools, and for what ends. Professional developers would benefit here from their own set of core practices for working with science educators. Still, this agenda would have to be supported by a vision of ambitious teaching and a focus on core practices. Using the shared language and images of teaching that support learning, it may be possible to engineer more productive socioprofessional relationships and routines that allow participants' practices to become an object of inquiry and improvement.

Recommendation: **Study both the formal and the informal networks of teachers as contexts for professional learning.**

Studying the arrangements described in the previous section means turning an eye toward *groups* of educators, rather than looking exclusively at individuals' participation and change. In her review of the literature on systemic instructional improvement, Resnick (2009) concluded that "the two most promising routes to altering the status quo appear to be the development of social capital within schools and the systematic introduction of tools and routines that have the power to directly change classroom practice and thereby increase learning" (p. 191). We suggest that the improvement of practice is best cultivated and studied at the level of a committed partnership of teachers who open up their practice to one another and experiment with new forms of tasks, talk, and tools over months and years. These are more reasonable timescales for the advancement of effective forms of pedagogy. With key resources and guidance, these partnerships can become knowledge-building communities whose problem-posing and problem-solving routines inform the development of such practitioner groups in other settings. When groups of professionals (teachers, instructional coaches, or district curriculum coordinators) act together, a more diverse set of analytic tools can be used by researchers—such as organizational learning or social networking theories—to understand how change and innovation happen at the scale of the community.

Conclusion

This chapter has leveraged scholarship from a number of research fields to suggest a new vision for science teaching and learning. Translating this vision into practice will require that the researcher community and the practitioner community work together for the continual improvement of teaching while also finding ways to systematically support the career-long development of individual educators. These proposals will require a cultural shift in how teaching is conceptualized. Popular images continue to convey the idea of accomplished teaching either as a set of skills accumulated through on-the-job experiences or as the inevitable outcome of recruiting the "best and brightest" into the profession. The research on science teaching, however, does not support this. If we shift the conversation from individual exceptionalism to groups of professionals (researchers as well as educators) who are willing to learn together and who maintain an uncompromising focus on student thinking, then rigorous and equitable instruction can be defined, modeled, and advanced by these communities. Put another way, ambitious teaching may become the norm rather than a rarity.

In this chapter we have focused on the ways in which teachers interact with learners regarding subject matter. Teaching cannot improve, however, unless there is an infrastructure to accommodate the effort. This means that some familiar conditions of schooling must change for ambitious teaching to gain a foothold in science classrooms. For example, the specter of high-stakes testing hangs over the heads of both teachers and students, leveling their aspirations for meaningful learning. If assessments of all kinds do not improve with regard to what is measured and how learning is measured, then they will remain a drag on the entire educational system. There are more items on this list, including encyclopedic and unconnected curricula that teachers feel they must "cover," unacceptably large class sizes, a lack of planning time, a dearth of skilled instructional coaches, and few opportunities to work with colleagues. These features of the working life of U.S. educators stand in contrast to the working life of teachers in the world's highest achieving countries. The only way forward is to coordinate changes in instruction with changes in curriculum, assessment, professional development, school leadership, and of course initial training.

Our aim in this chapter has been not to advocate for a new pedagogical orthodoxy, but rather to cultivate responsive mechanisms for the renewal of science teaching. Such proposals for prioritizing instructional practices in research and in our educational system should be heavily scrutinized, given that there is much more to the work of teaching and more involved in the development of effective, caring, and reflective practitioners. Perhaps by the time the next version of this *Handbook* is written, we will have collectively embraced the critique and the promise described here to change how we help young learners engage with science.

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