Sociocultural approaches to learning science in classrooms

Final Draft of a Report to the National Research Council Committee on Science Learning K-8

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1/16/2006

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This paper will review literature on learning science in K-8 classrooms by asking and answering three major questions: **Who learns science in classrooms? How is science learned in classrooms? What science is learned in classrooms?**[1] These questions will be addressed from a sociocultural perspective, which means that the unit of analysis (both theoretically and methodologically) should include both the individual and the social world (Vygotsky, 1978; Wertsch, 1985). Thus, the proposed connections between causes and outcomes must include contextual as well as psychological factors (Rogoff, 1998).

Sociocultural theory provides many conceptual tools for studying the processes of learning science in educational settings. In addition, methodological tools from sociolinguistics have been incorporated that facilitate analysis of complex educational environments with multiple causal influences on learning (Eisenhart, Finkel, & Marion, 1996; Gee, Michaels, & O'Connor, 1992; Green, Dixon, & Zaharlick, 2003; Kelly & Green,1998).

Rogoff's (2003) framework for recontextualizing human development is consistent with a sociocultural approach and will be used to guide our answers to the first question: Who learns science in classrooms? Instead of locating development within the heads of isolated individuals or as a simplistic causal system of cultural influences on development, she argues that development needs to be viewed as a process of participation in community activities.

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[1] We have focused on research articles in peer reviewed journals about students in grades K-8, as much as possible. However, we have also included some studies of older students and studies described in book chapters. Also, in some instances, we have drawn from the literature in mathematics education.

> Rather than individual development being influenced by (and influencing) culture, from my perspective, people develop as they participate in and contribute to cultural activities that themselves develop with the involvement of people in successive generations (p. 52)

Rogoff conceptualizes this process of participation as occurring on at least three levels: personal, interpersonal, and cultural/institutional. Like Olson (2003), she argues that an adequate notion of human development has to include the history and analysis of the institutions (such as schools and scientific communities) that affect and are affected by the developmental trajectories of individuals and their interpersonal relationships. These levels never operate alone (although for analytic purposes we may need to focus on each level separately). In fact, they are inherently interwoven in all human activities (including mental activities). One way to depict these levels is to view them as if you were taking scenic photographs of the same landscape using a variety of lenses: close-up for the personal level, using a slightly wider angle for the interpersonal, and using a widest angle for the cultural/institutional level. Of course, since activities are not static, you would need to think about the levels (or different lenses) occurring simultaneously in a film and not a series of photographs.

A second major framework for our analysis comes from an article by Engle and Conant (2002), which will be used to organize our answers to the second question. Engle and Conant have characterized effective learning environments for science by differentiating between engagement; disciplinary engagement; and productive disciplinary engagement. They argue that the preconditions for productive disciplinary engagement involve: providing appropriately challenging activities; allowing students to take authority over their learning but making sure that their work can be scrutinized by others (teachers and students), using criteria acceptable to scientific disciplines (e.g., logical consistency; explanatory power). In addition, students need to have access to the resources they need (texts, laboratory equipment, recording devices) to evaluate their claims and communicate them to others.

In addition, Engle and Conant define engagement in terms of students actively speaking, listening, responding, and working and high levels of on-task behavior. Disciplinary engagement expands to include scientific content and experimental activities (including argumentation based on logic and data patterns). Productive disciplinary engagement encompasses the additional criteria of demonstrated change over time in student investigations; complexity of argumentation; and use of previous investigations to generate new questions, new concepts, and new investigations.

Finally, our third framework comes from the discipline of social studies of science (e.g., Latour, 1987; Pickering, 1995). The nature of scientific disciplinary communities becomes important as we try to decide **what counts** as learning science. As Shulman and Quinlan argue (1996, p. 399), “what counts as knowing a subject is pivotal to how we theorize about it, how we study it, and how we attempt to influence its development.” This framework will be especially useful as we move to the last of our three questions. We will argue that psychological, linguistic, sociological, or anthropological accounts of learning science in classrooms are not sufficient for helping us determine whether students are learning how to do a lesson or how to do science (Jimenez-Aleixandre, Rodriguez, & Duschl, 2000). Thus, we believe that incorporating some notions from the social studies of science helps us better understand what aspects of authentic scientific practice can be learned in classroom settings.

Who learns science in classrooms?

This question will be answered by examining research that focuses on schools as bureaucratic institutions (cf. Olson, 2003) in which students are assigned to different grade levels (usually based on age), different educational tracks (based on teacher’s grades, achievement scores, parental requests) and/or special education classes versus regular education classes (based on referrals and standardized test scores). How these institutional arrangements encourage or hinder student learning of science has been the focus of a substantial body of educational research conducted from a sociocultural perspective. In addition to institutional arrangements, more informal social interaction patterns also play a role in affording or constraining student learning of science. These interpersonal dynamics often operate in concert with tracking or special education placement decisions. Finally, students may respond (to the messages they receive from others about their supposed lack of ability to learn science) by internalizing those messages and failing to persist when faced with challenging science tasks. A good deal of sociocultural research has addressed these questions of equity and access to science learning in schools (e.g., Eisenhart, Finkel, & Marion, 1996; Tobin, Elmesky, & Seiler, 2005; Yerrick & Roth, 2005). This is also true for research on equity in mathematics education (Nasir & Cobb, 2002).

The institutional level of analysis. The most ubiquitous organizational structure of schools is age-grading. If students of a given age/grade are seen as not capable of learning challenging science content and procedures by people with decision-making power, then their access to authentic science during school hours is limited. Unfortunately, elementary science curriculum materials have been constrained by poorly understood notions of developmental constraints on science learning (Metz, 1995). As a result, elementary school teachers (many of whom have limited science background themselves), may restrict their instruction to vocabulary development, poorly designed hands-on science kits, and disconnected lessons driven more by content than by linkages to major science concepts, models or practices (e.g., batteries and light bulbs). Nevertheless, several programs of research have consistently contradicted the notions that elementary school children are incapable of engaging in genuine scientific practices (such as argumentation, experimentation, data representation, or abstract thinking) (e.g., Brown, 1997; Cornelius & Herrenkohl, 2004; Lehrer & Schauble, 2004).

In addition, science instruction in preschools and elementary schools occurs much less often than instruction in the subjects that have been the focus of high stakes testing: literacy and mathematics. Thus, several forces work together to restrict and water-down science instruction in preschools and elementary schools: teachers' inadequate training and beliefs about developmental constraints on abstract thinking and scientific problem solving skills in young children; curriculum that falsely assumes that young children are incapable of understanding genuine scientific practices; and lack of time and resources for a subject that has not been the focus of high stakes tests.

Upper level grades in elementary schools, middle schools, and high schools often attempt to cope with the challenges of a heterogeneous student population by designing homogeneous academic tracks or by excluding students with disabilities from many or all regular classrooms. Although this practice can have positive outcomes when students receive instruction that is tailored to their own individual needs, it can have negative outcomes as well. For example, low-achieving students may be excluded from science classes, especially at the high school level, because of their lack of prerequisite knowledge and skills and/or because students, parents, and counselors assume that challenging science courses are only appropriate for those students who are headed for four-year colleges or for middle class students or for students whose native language is English (Eckert, 1990; Gilbert & Yerrick, 2001).

Students with disabilities may be taught science content in either mainstreamed classrooms or self-contained classrooms but they are rarely afforded the chance to engage in authentic scientific inquiry. Palincsar and Magnusson and their colleagues have conducted a program of research that successfully challenges the notion that students with disabilities can not be successful in inquiry instruction (Palincsar et al., 2000; 2001). They have found that students with mild learning disabilities, under appropriate instructional conditions, can learn science as well as their normally achieving peers.

Often students in urban schools with histories of underachievement, especially students whose native language is not English, are frequently excluded from challenging science instruction. Several programs of research in urban elementary and middle schools have demonstrated that these children are capable of engaging in sophisticated scientific activities with appropriate instructional support, despite their spotty achievement histories or lack of access to science in the early grades (e.g., Ballenger, 1997; Brown et al., 2005; Engle & Conant, 2002; Hogan & Corey, 2001; Kelly & Brown, 2003; Rosebery, Warren, & Conant, 1992; Varelas, Luster, & Wenzel, 1999).

Whereas schools, as institutions, may systematically exclude some students from authentic science instruction (thus limiting their science learning) in classrooms where science instruction occurs, interpersonal dynamics may also effectively exclude students from anything but superficial science instruction. In addition, it is important to mention that our sociocultural perspective is not a social-determinist theory. Thus, while the social context (institutional or interpersonal) may position some students as “incapable” of learning science, student reactions to this characterization will vary. Some students may position themselves to resist by showing their capabilities in science whereas others may appropriate the messages they receive and conclude that science is just not for them (Brown et al. 2005; Ritchie, 2002; Smardon, 2004).

Eisenhart, Finkel, and Marion (1996) have addressed this issue in some detail in their review article. Some of the factors that they identify as contributing to the under representation of females, working class males, and people of color in science include: media stereotypes of scientists; the lack of connection with female and non-Western interests and backgrounds; and the climate of degree programs and high status scientific professions that systematically excludes females (Eisenhart & Finkel, 1998).

Interpersonal level of analysis. Understanding why people from different economic, ethnic, racial, or linguistic backgrounds may have trouble communicating with each other and working productively in schools is not merely an academic question. We won't be able to fully understand what poor students in urban schools are capable of learning about science if we don't understand what students and teachers in public schools are dealing with on a daily basis. For example, school faculties in urban districts continue to be predominantly middle class, monolingual, white and female. Unfortunately, the gap between the backgrounds of teachers and their students often results in beliefs (by both groups about each other) that are counter-productive to effective instruction (Gilbert, 1997; Rueda & Moll, 1994). For example, preservice teachers often view urban schools as under-resourced, violent places filled with unmotivated students who need to be controlled more than understood, instructed, or appreciated (Haberman, 1991; Tiezza & Cross, 1997).

This gap interferes with learning among poor students and students of color in all subject areas because it turns cultural and linguistic differences into barriers to communication (Erickson, 1993). Case studies of individual teachers, such as Jen Beers (2005), illustrate the ways in which the beliefs and behaviors of both teachers and students can maintain (social, linguistic, and material) barriers to effective instruction. However, Jen's situation was unusual because she worked with a group of science education researchers and teachers who supported her attempts to improve her instruction. As a result, Jen was able to adapt her instruction (within a short period of time) to engage her high school students and to teach them important scientific literacy skills.

Goodnow (1990) has argued that learning is dependent upon cultural values (e.g., what's worth knowing) as well as cognitive processes. She proposes that institutional structures and interpersonal interactions send not-so-hidden messages to students about what is "too difficult," "too dangerous," "too painful," "too foreign" for them to understand. Thus, students who have limited access to appropriately challenging curriculum materials, laboratory equipment, and/or instruction by teachers who are ill-prepared or unwilling to adapt texts or tools to meet their students' needs are likely to appropriate these messages and conclude that science is not for someone like them.

Goodnow's argument is well-illustrated by a sequence of instructional discourse displayed in Gilbert & Yerrick (2001) from a lower-track high school science class. The teacher begins the exchange with open-ended directions for an inquiry activity but ends the discussion with his students by using highly directive questions for them to answer in a very restricted fashion. The authors argue that this conversational sequence occurred because the students resisted his invitation to engage in an unfamiliar open-ended exchange. They were more used to a mixture of tight behavioral control and boring academic tasks. Thus, interaction patterns, once established, may be resistant to change without a concerted effort on the part of all members of a classroom community (as was the case with Jen Beers).

Ethnographic studies of classroom communication have documented numerous examples of students who appear to be learning science but are, instead, very good at communicating with their teachers by doing the lesson (but not doing the science) (Brown et al., 2005; Ritchie, 2002; Smardon, 2004). In contrast, studies also document that some students are actually doing the science but refusing to show their capabilities to teachers who appear to believe that they are not capable enough to do the required work (Brown et al., 2005; Smardon, 2004).

Studies of student beliefs and attitudes towards their schools and their teachers show that the students are very aware of how they are being viewed and treated. For example, Gilbert and Yerrick (2001) documented the reactions of teachers and students to the tracking system in their high school science classes. One teacher who instructed students in honors classes as well as in the lower track, general earth science classes reported large differences in motivation, background knowledge, and parental encouragement between these two groups (that also differed in race, social class, and ethnicity).

> I like my honors students; they’re going to learn a lot almost regardless of what I do. Sometimes on my worst days it seems like just the opposite

with the general. It seems like they're not going to learn anything regardless of what I do (p. 586).

His students also held negative views of him. They saw his treatment of them as condescending (by breaking down material, treating them as incapable of learning, refusing to allow them access to the chemical and equipment that other students use in their classes): "It's lack of respect for us, really" (p. 587).

One way for teachers to understand cultural differences in learning is to reify typical interaction patterns as "cultural learning styles." For example, Lee and Fradd (1996) examined the communication patterns of several cultural groups of fourth grade students (English, Spanish, and Haitian Creole speakers) while the students were conducting experiments with a variety of science content. They found different communication patterns being employed in the three linguistic groups in terms of common participant structures (e.g., use of simultaneous or sequential speech). This finding is consistent with earlier work on communication patterns in segregated classrooms (e.g., Lipka, 1998; Tharp & Gallimore, 1988). Thus, suggestions for providing culturally compatible instruction could follow from this body of research. Nevertheless, there is a danger in over-simplifying cultural communication practices.

Gutierrez and Rogoff (2003) critically evaluate the notion of "cultural learning styles." They argue that the reification of cultural differences in values, beliefs, and interaction patterns into "cultural styles" attributed to a group of people can result in discriminatory practices that are based on ethnocentrism more than on culturally-sensitive pedagogy. They are concerned that this approach can essentialize the characteristics of groups of people as if they applied to all group members and were unresponsive to differing times, places, and social contexts. This approach, they feel, can be equally counter-productive if it means that groups of students are treated as if they were homogeneous in interests, communication style, educational aspirations, etc. (Similar concerns can also be raised for students who have been labeled as “learning disabled” as research by McDermott, 1993, has shown.) Instead, they recommend that teachers avoid stereotyping or generalizing about groups of students and focus on characterizing students’ motivations and understandings at different points in time and in a variety of situations. They also suggest that teachers avoid making simplistic causal attributions about their students’ academic successes and failures. Gutierrez and Rogoff do not think that focusing on student deficits or differences per se would be useful for teachers. In addition, they suggest that teachers approach poor and minority students in the same way that they might approach middle class students: with an open mind; with sensitivity to individual differences and situational affordances and constraints; and with the recognition that students everywhere approach learning situations with a variety of attitudes and understandings (similar recommendations for mathematics education were expressed by Nasir & Cobb, 2002).

The program of research by Warren and Rosebery and their colleagues at the Cheche Konnen Center has demonstrated that urban, ESL (English as a Second Language) students can effectively engage in high level scientific reasoning and problem solving if taught by teachers who share their cultural background and/or if taught in ways that respect students' interests and sense-making (e.g., Ballenger, 1997; Hudicourt-Barnes, 2003; Warren et al., 2001). This message is echoed by Lemke (1990). For example, Hudicourt-Barnes used her knowledge of the traditional Haitian form of talk called "bay odyans" ("chatting") to foster arguments or "diskisyon" (discussion) in science classrooms for Haitian students. She worked with other members of the Cheche Konnen Center to help poor bilingual students build on their interest in talking and in exploring phenomena in the world by using their indigenous form of argument (and their interests in African drums, etc.) as a link to more conventional scientific investigations of the physics of sound, the reproductive cycle of snails, and the causes of mold.

Collins, Palincsar and Magnusson (2005) document similar negative attitudes about students with specific disabilities. Nevertheless, their program of research has been able to demonstrate that a guided inquiry approach to instruction contradicts the predictions of some educators concerning the potential limits on science learning by these students (e.g., Palincsar, Collins, Marano, & Magnusson, 2000; Palincsar, Magnusson, Collins, & Cutter, 2001). Instead of localizing the source of learning difficulties in individuals, their approach sees learning (or failure to learn) as the result of interactional dynamics in the classroom.

As Eisenhart, Finkel, and Marion propose (1996), sociocultural approaches emphasize the importance of identity in motivating students to learn difficult content in science and other disciplines (Nasir and Cobb, 2002). A sociocultural approach to identity requires a reflexive relationship between the social forces (historical, cultural, and interpersonal) that shape identity and the agency of individuals who author their own identities (Holland, Lachicotte, Skinner, & Cain, 1998).

Personal level of analysis. One study reviewed above (Brown et al., 2005) conducted in an urban fifth grade classroom and two studies conducted in urban high schools (Smardon, 2004; Tabak & Baumgartner, 2004) investigated the over-looked but critically important topic of students' identities as science learners. Two of the studies (Brown et al., 2005; Smardon, 2004) found that teachers may position some students as proficient science students and others as deficient science students based on limited or distorted information about their actual scientific literacy (e.g., use of scientific jargon without sufficient understanding). This practice of positioning can have detrimental effects on a student's sense of themselves as well as on teachers' expectations (cf. Gilbert & Yerrick, 2001).

Tabak and Baumgartner (2004), in contrast, proposed a connection between a teacher's instructional practices, classroom participant structures (e.g., turn-taking patterns, nature of prompts, discursive practices) and students' sense of intellectual authority. They speculated that teachers who play a monitoring role in the classroom would be more likely to reserve intellectual authority for themselves (or for course materials such as textbooks) whereas teachers who fostered other participant structures such as mentoring or partnering would be more likely to share intellectual authority with their students.

Thus, they proposed that there might be a close connection between interpersonal interactions in the classroom and students' sense of themselves. The study by Tabak and Baumgartner suggests that teachers and students may co-create classroom communities that foster or impede the development of positive learning identities.

The literature we have reviewed above demonstrates that it is possible (although unfortunately rare) for teachers and students to co-create positive learning communities for science in urban, suburban, and rural elementary, middle, and high schools. Engaging students in the content and process of scientific inquiry is a necessary first step. However, just focusing on superficial indices of "engagement" may not be sufficient for achieving classroom communities that foster long-term changes in students' investment in learning science. Here's where Engle and Conant's (2002) characterization of "productive disciplinary engagement" becomes relevant. In our next section we will use their framework to review literature on how science is learned in classrooms.

How is science learned?

Engle and Conant (2002) argue that the preconditions for productive disciplinary engagement involve: providing appropriately challenging activities; allowing students to take authority over their learning but making sure that their work can be scrutinized by others (teachers and students), using criteria acceptable to scientific disciplines (e.g., logical consistency; explanatory power). In addition, students need to have access to the resources they need (texts, laboratory equipment, recording devices) to evaluate their claims and communicate them to others. We agree that these criteria define high-level science instruction and learning, from a sociocultural perspective.

In addition, Engle and Conant define engagement in terms of students actively speaking, listening, responding, and working and high levels of on-task behavior. Disciplinary engagement includes scientific content and experimental activities (including argumentation based on logic and data patterns). Finally, productive disciplinary engagement is the additional criteria that include demonstrated change over time in student investigations; complexity of argumentation; and use of previous investigations to generate new questions, new concepts, new investigations. In our summary below, we will highlight the studies that examined disciplinary engagement and address the issue of productive disciplinary engagement when we answer the final question (What is learned?).

One study (Cornelius & Herrenkohl, 2004) explicitly employed the notion of productive disciplinary engagement and connected it to analyses of participant structures and discourse. In their study of a pair of sixth grade girls investigating sinking and floating, they found evidence that the students took an active role in generating ideas, engaging in scientific argumentation with their peers, and learning how to use persuasive discourse to convince others of the validity of those ideas.

Other studies have demonstrated that K-8 students in urban as well as suburban public schools can engage in scientific activities such as investigating floating and sinking (Herrenkohl, Palincar, DeWater, and Kawasaki, 1999; Lee &

Fradd, 1996; Palincsar et al., 2001; Varelas, Luster, & Wenzel, 1999); ecology (Hogan & Corey, 2001; Rosebery et al., 1992); the classification and growth of plants and animals (Brown et al., 2005; Lehrer & Schauble, 2004; Lehrer & Schauble et al., 2000; Warren & Rosebery, 1996); motion down inclined planes (Lehrer & Schauble et al., 2000); and density functions of material kind (Lehrer & Schauble et al., 2001).

Most of the above studies employed ethnographic case analyses of a small number of classrooms and/or groups of students. A few studies employed a mixture of quantitative and qualitative analyses (Herrenkohl & Guerra, 1998; Lee & Fradd, 1996; Palincsar et al., 2001). The smallest number of studies focused on students in grades K-2 (e.g., Lehrer, Schauble & Petrosino, 2001); the largest number of studies examined students in grades 5 or 6.

These studies tend to define disciplinary engagement differently and tend to employ different tasks and/or focus on different participant populations making it difficult to easily summarize results across studies (other than to show that young children, poor students, and students with mild disabilities are capable—under the right conditions—of high-level disciplinary engagement with scientific concepts and procedures in formal educational settings). Most of the studies reviewed demonstrate disciplinary engagement can be achieved but few appear to demonstrate productive disciplinary engagement (notable exceptions include Herrenkohl et al., 1999; Lehrer, Schauble, Strom & Pligge, 2001; Palincsar, Magnusson, Collins, & Cutter, 2001; Rosebery, Warren & Conant, 1992).

What science is learned?

When one tries to answer this question, it quickly becomes apparent that sociocultural theories of learning need to be supplemented by other literatures to help us decide whether students are learning how to do a lesson or how to do science (Jimenez-Aleixandre, Rodriguez, & Duschl, 2000). In our discussion above, we have used Engle and Conant's (2002) definition of productive disciplinary engagement as well as the conditions necessary for fostering it. Unfortunately, this definition is quite vague and includes many activities that scientists would not recognize as "disciplinary": such as classifying plants and animals using predefined criteria; conducting predefined tests of the variables necessary and sufficient for buoyancy; etc. Here's where work in the social studies of science is useful.

A word of caution, however, is necessary. Basing educational prescriptions or norms on scientific descriptions can be risky (Kelly, 2005). This is due, in part, to the multiplicity of interpretations of science and scientific knowledge in the social studies of science literature, which could be used to justify an extreme version of relativism for education ("anything goes"). However, our aim is not to use the social studies of science literature to prescribe educational practices. Instead, we use it to highlight existing educational programs that come closest to a version of scientific practice that has been outlined by a selected sample of this literature. We hope that this perspective on classroom instruction can shed light on crucial judgments of productive disciplinary engagement.

One valuable source of information from the science studies literature is the work of Pickering (1995). Pickering focuses on the dual nature of agency in science: from humans and the material world. As scientists make plans to achieve goals in their research, they encounter resistances from the world that force them to accommodate their actions, including the design or redesign of tools that enable them to better tune their actions with feedback from the world. This constitutes “the dance of agency . . . a dialectic of resistance and accommodation” (p. 22). He refers to this dance as “the mangle of practice” (p. 23). By including time in the picture, Pickering argues that scientific investigations are unpredictable: often leading in unforeseen directions. Thus, the goals of science are emergent.

What does this picture of science tell us about classrooms that foster productive disciplinary engagement that the account by Engle and Conant (2002) could not provide? In Engle and Conant’s framework, criteria from psychological task analysis and curriculum design seems to guide judgments of productive disciplinary engagement (e.g., increasingly complex conceptual networks or increasingly elaborated, articulated, and integrated arguments). If Pickering is correct, then productive disciplinary engagement among scientists would be evaluated quite differently and might look rather unpredictable and chaotic in the short term. Shulman and Quinlan (1996) propose that criteria for what counts as knowing a subject should come, in part, from the disciplines (such as the natural sciences) and not just from a field like educational psychology. Using criteria from the social studies of science might provide an alternative view of productive disciplinary engagement. For example, productive engagement might depend upon the design of tools that allow student investigators to better tune their actions with feedback from the world. In addition, students' goals and interests may need to be considered when planning investigations and teachers may have to allow for cycles of investigation that might be required to resolve disagreements about the interpretations of any particular research project. At least three programs of educational research seem to us to meet Pickering's criteria for authentic and productive scientific endeavors: Lehrer and Schauble and their colleagues; Warren and Rosebery and their colleagues; and Herrenkohl and Palincsar and their colleagues.

For example, Lehrer, Schauble, Carpenter, and Penner (2000) described a sequence of classroom lessons in elementary school classrooms (2nd and 3rd grade), in which one group of students first investigated inclined planes and free fall and then investigated plant growth. During the first investigation, students found that they needed to invent the notion of steepness to compare ramps and discovered that the ramps could be viewed as right triangles that varied in angle of inclination. Pickering would call this triangle a tool that the students created to measure and record the material world's agency. In the second investigation, this same group of students plotted growth curves of Wisconsin fast plants. Thus, in the first investigation, the goal was to understand the relationship between ramp steepness and object speed; in the second investigation, the goal was to understand the rate of growth of plants. On the surface, these disparate activities would seem unlikely to demonstrate productive disciplinary engagement, using standard educational psychology criteria, because they may not appear to be connected to the same content. Nevertheless, as students tried to explain the changes in growth over the life-span of a plant, which on a graph appears to have a S shape, one of them realized that using the right triangle from their earlier work with ramps would help them quantify the slope of a graph at some key intervals. Thus, the triangle became not just a tool for measuring the slope of a ramp; it was used to model rate of change at different places on a growth curve. This example seems to parallel some of Pickering's requirements for authentic scientific practice: its unpredictable nature (as new questions emerge, new tools or old tools for new purposes are employed to record the agency of the material world) and its goal-driven, planful nature (students' wanted to know if cars move down very steep ramps faster than less steep ramps; they wanted to know how to describe their plants' growth).

In a similar fashion, Rosebery, Warren, and Conant (1992) documented the investigations of 7th and 8th graders in an urban middle school. These students began their explorations with their own research question about the water quality and taste of two school drinking fountains and then used the tools that they had found (as well as new ones) to evaluate the quality of water in a local pond. Here too, you can see the emergent quality of these investigations that were driven by students' questions, plans, and goals and the importance of tools for measurement in those investigations.

Finally, Herrenkohl, Palincsar and their colleagues (1999) have demonstrated productive disciplinary engagement among members of two upper elementary school classrooms, located in two different schools (one of which served a poor, urban population). As in the research summarized immediately above, students engaged in multiple cycles of theorizing, experimentation, reflection, discussion, and theory revision, guided by images of genuine scientific practice afforded by the social studies of science literature. They characterized the sequence of inquiry as "not linear; clarification and consistency occurred through an iterative process in which students tried out a range of explanations and negotiated the unique features of a theory" (p. 487). This nonlinear process contrasts with the more typical sequence required in science classrooms that attempt to foster experimentation (e.g., when predictions precede experiments and are followed by conclusions).

A key similarity among the above programs of research was the use of design experiments to leverage achievement gains as well as positive attitude and motivational changes among diverse (as well as mainstream) learners (Brown, 1992, 1997; Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003; Ford & Forman, in press; Schoenfeld, in press). For these educational researchers, leveraging achievement (according to conventional and unconventional measures) is the aim of their investigations not merely the goal of replicating genuine scientific practices in classrooms. Institutional support for design experiments varies from one school to the next, one district or state to the next. Yet, without institutional support for changes in tracking, inclusion, or professional development, design experiments can not survive long enough for teachers and researchers to document their strengths and weaknesses, learn from inevitable mistakes, or travel from one classroom or school to the next.

Now that we have addressed our three original questions (Who learns science?, How is it learned?, What is learned?) we are ready to draw some general conclusions about the literature we have reviewed (its strengths and limitations) and recommendations for future research.

Conclusions and Recommendations

We have drawn from research literature (which was based on sociocultural theory) to draw conclusions about students' learning of science in formal educational settings. In this literature, several views of science are represented: science-as-logic; science-as-theory change; science-as-practice (Lehrer & Schauble, in press). Nevertheless, the third view of science predominates, which makes it consistent with the theories of major sociocultural writers like Rogoff and compatible with some of the social studies of science literature (e.g., work by Pickering). In addition, several views of learning are represented: learning-as-acquisition versus learning-as-participation (Sfard, 1998). The second view of learning, however, also predominates. In addition, we agree with several of the authors we reviewed that theories of science learning need to come from linguistics, anthropology, sociology, and the history and philosophy of science as well as from psychology. Thus, in our view, science learning occurs as much between people and between people and cultural artifacts as it occurs within individuals. As a result, we feel that it is important to study science learning as a collective endeavor.

Finally, we found that most of the studies we reviewed employed ethnographic methods (sometimes in combination with quantitative and/or experimental methods) and many of the most promising investigations of productive disciplinary engagement occurred in the context of design experiments. Because of these methods, most of the studies were small in scale—typically case studies of a few students or a limited number of classrooms. However, these small scale studies provided rich descriptive information about the nature of the settings examined (people, instructional resources, interaction patterns, and discourse). Most were also short term (a few weeks or months) and were able to report just a fraction of the data collected. Very few studies were able to examine long term change over years of schooling. Thus, information about developmental trajectories within complex social contexts is quite limited.

The largest section in our review is the first one about access to science learning. This is due, in part, to a continuing interest in using sociocultural theory to investigate issues of diversity and equity in education (Nasir & Cobb, 2002; Eisenhart et al., 1996). Much of the literature about access to appropriate instruction comes from work done in high school settings where educational tracking is more frequently employed to create homogeneous groups, often effectively excluding many students from challenging material and/or high expectations about their likely success. Of course, informal systems for tracking also occur in elementary and middle schools but their impact may be more difficult to detect and document, except in the areas of special education and bilingual education. Another way students are excluded from engaging in challenging activities with science is the limited exposure most students get to science in the early grades (as a result of the pressures of high stakes testing in math and literacy; teachers' inadequate training and beliefs about developmental constraints; and poorly design curriculum).

As you have seen in our second section about how learning occurs, this research has been able to document (using a wide variety of indices) different modes of engagement by students during science instruction. This area of research, although relatively new, has been quite descriptively rich and full of methodological innovations. This work has demonstrated that young students, students with diagnosed learning disabilities, poor students, students of color, and bilingual speakers are quite capable of high level disciplinary engagement with appropriate scaffolding from their teachers and peers. Unfortunately, as we have shown in our first section, too many students miss out on these important opportunities. In addition, as we have discussed in our third section, very few students have the experience of productive disciplinary engagement over a series of weeks, months, or years. Because adults who are not scientifically trained tend to show many of the same reasoning difficulties and misconceptions as children and adolescents, most students are unlikely to learn much science outside of formal educational settings. Thus, changing the culture of the classroom is necessary for improving scientific literacy in the nation.

Based on our review of the literature of sociocultural studies of science learning, we make the following recommendations:

- More research is needed on science learning in K-3 classrooms and in classrooms serving students with disabilities.
- More research is needed on instructional approaches that have been successful with young students, poor students, students of color, students with disabilities, and bilingual students.
- More research is needed on interventions that are capable of changing teachers' beliefs about, attitudes toward, and practices with young children, poor and minority students and students with disabilities.
- A broader range of research methods needs to be encouraged so that learning over time in complex social environments can be studied. Ethnographic research and design-based research may be necessary to help us depict and foster the most productive learning settings for students. Improved methods for summarizing results across multiple case studies are needed.
- More research on science learning-as-practice needs to be done to broaden and deepen our understanding of the conditions necessary for fostering productive disciplinary engagement in science. Research that helps us better understand the potentially useful parallels between the practices of scientists and the practices in science classrooms is especially needed.
- Collaborations with researchers and educators with diverse disciplinary backgrounds should be encouraged because investigations capable of examining cultural, institutional, interpersonal, as well as personal

interactions over time with challenging science materials are needed to further the research agenda in science learning.

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