

CHAPTER 19

Project-Based Learning

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Any teacher or parent can tell you that many students are bored in school. But many of them tend to assume that boredom is not a problem with the best students, and that if students tried harder or learned better they wouldn't be bored. In the 1980s and 1990s, education researchers increasingly realized that when students are bored and unengaged, they are less likely to learn (Blumenfeld et al., 1991). Studies of student experience found that almost all students are bored in school, even the ones who score well on standardized tests (Csikszentmihalyi, Rathunde, & Whalen, 1993). By about 1990, it became obvious to education researchers that the problem wasn't the fault of the students; there was something wrong with the structure of schooling. If we could find a way to engage students in their learning, to restructure the classroom so that students would be motivated to learn, that would be a dramatic change.

Also by about 1990, new assessments of college students had shown that the knowledge they acquired in high school remained at a superficial level. Even the best-

scoring students, those at the top colleges, often had not acquired a deeper conceptual understanding of material – whether in science, literature, or math (Gardner, 1991). Educators still face these critical problems today.

Learning sciences research provides a potential solution to these problems. Drawing on the cognitive sciences and other disciplines, learning scientists are uncovering the cognitive structure of deeper conceptual understanding, discovering principles that govern learning, and showing in detail that schools teach superficial knowledge rather than deeper knowledge. Drawing on this research, many learning scientists are developing new types of curricula, with the goal of increasing student engagement and helping them develop deeper understanding of important ideas. Our own contribution is articulating the features of *project-based learning* (Blumenfeld et al., 2000; Krajcik et al., 1994). Project-based learning allows students to learn by doing and applying ideas. Students engage in real-world activities that are similar to the activities that adult professionals engage in.

Project-based learning is a form of situated learning (Greeno, this volume) and it is based on the constructivist finding that students gain a deeper understanding of material when they actively construct their understand by working with and using ideas. In project-based learning, students engage in real, meaningful problems that are important to them and that are similar to what scientists, mathematicians, writers, and historians do. A project-based classroom allows students to investigate questions, propose hypotheses and explanations, discuss their ideas, challenge the ideas of others, and try out new ideas. Research has demonstrated that students in project-based learning classrooms get higher scores than students in traditional classrooms (Marx et al., 2004; Rivet & Krajcik, 2004; William & Linn, 2003).

Project-based learning is an overall approach to the design of learning environments. Learning environments that are project-based have five key features (Blumenfeld et al., 1991; Krajcik, et al., 1994; Krajcik, Czerniak, & Berger, 2002):

1. They start with a driving question, a problem to be solved.
2. Students explore the driving question by participating in authentic, situated inquiry – processes of problem solving that are central to expert performance in the discipline. As students explore the driving question, they learn and apply important ideas in the discipline.
3. Students, teachers, and community members engage in collaborative activities to find solutions to the driving question. This mirrors the complex social situation of expert problem solving.
4. While engaged in the inquiry process, students are scaffolded with learning technologies that help them participate in activities normally beyond their ability.
5. Students create a set of tangible products that address the driving question. These are shared artifacts, publicly accessible external representations of the class's learning.

In the next section, we summarize the learning sciences theory behind project-

based learning. Our own efforts have emphasized applying project-based methods to science classrooms, so in the section after that, we show how our work builds on project-based learning principles. Based on over ten years working in science classrooms, we have learned several important lessons about how to apply project-based learning in schools, and in the bulk of the chapter, we group our lessons around the five key features of project-based learning. We close by discussing issues that we encountered in scaling up our curriculum.

Theoretical Background of Project-Based Learning

The roots of project-based learning extend back over a hundred years, to the work of educator and philosopher John Dewey (1959), whose Laboratory School at the University of Chicago was based on the process of inquiry. Dewey argued that students will develop personal investment in the material if they engage in real, meaningful tasks and problems that emulate what experts do in real-world situations. In the last two decades, learning sciences researchers have refined and elaborated Dewey's original insight that active inquiry results in deeper understanding. New discoveries in the learning sciences have led to new ways of understanding how children learn (Bransford, Brown, & Cocking, 1999). We build on four major learning sciences ideas: (1) active construction, (2) situated learning, (3) social interactions, and (4) cognitive tools.

Active Construction

Learning sciences research has found that deep understanding occurs when a learner actively constructs meaning based on his or her experiences and interaction in the world, and that only superficial learning occurs when learners passively take in information transmitted from a teacher, a computer, or a book (Sawyer introduction, this volume). The development of understanding is a continuous process that requires students to construct and reconstruct what they know

from new experiences and ideas, and prior knowledge and experiences. Teachers and materials do not reveal knowledge to learners; rather, learners actively build knowledge as they explore the surrounding world, observe and interact with phenomena, take in new ideas, make connections between new and old ideas, and discuss and interact with others. In project-based learning, students actively construct their knowledge by participating in real-world activities similar to those that experts engage in, to solve problems and develop artifacts.

Situated Learning

Learning sciences research has shown that the most effective learning occurs when the learning is situated in an authentic, real-world context. In some scientific disciplines, scientists conduct experiments in laboratories; in others, they systematically observe the natural world and draw conclusions from their observations. Situated learning in science would involve students in experiencing phenomena as they take part in various scientific practices such as designing investigations, making explanations, modeling, and presenting their ideas to others. One of the benefits of situated learning is that students can more easily see the value and meaning of the tasks and activities they perform. When students do a science experiment by following detailed steps in the textbook, that's hardly any better than passively listening to a lecture. Either way, it's hard for them to see the meaning in what they're doing. But when they create their own investigation design to answer a question that is important to them and their community, they can see how science can be applied to solve important problems.

A second benefit of situated learning is that it seems to generalize better to a wider range of situations (Kolodner, this volume). When learners acquire information through memorization of discrete facts that are not connected to important and meaningful situations, the superficial understanding that results is difficult for students to generalize to new situations. When students participate in step-by-step science experiments

from the textbook, they don't learn how and where to apply these same procedures outside of the classroom. However, when students acquire information in a meaningful context (Blumenfeld et al., 1991) and relate it to their prior knowledge and experiences, they can form connections between the new information and the prior knowledge to develop better, larger, and more linked conceptual understanding.

Social Interaction

One of the most solid findings to emerge from learning sciences research is the important role of social interaction in learning (Collins, this volume; Greeno, this volume; Sawyer, this volume). The best learning results from a particular kind of social interaction: when teachers, students, and community members work together in a situated activity to construct shared understanding. Learners develop understandings of principles and ideas through sharing, using, and debating ideas with others (Blumenfeld et al., 1996). This back-and-forth sharing, using, and debating of ideas helps to create a community of learners.

Cognitive Tools

Learning sciences research has demonstrated the important role of tools in learning (Salomon, Perkins, & Globerson, 1991). Cognitive tools can amplify and expand what students can learn. A graph is an example of a cognitive tool that helps learners see patterns in data. Various forms of computer software can be considered cognitive tools because they allow learners to carry out tasks not possible without the software's assistance and support. For instance, new forms of computer software allow learners to visualize complex data sets (Edelson & Reiser, this volume). In such situations, we refer to the computer software as a learning technology.

Learning technologies can support students (1) in accessing and collecting a range of scientific data and information; (2) by providing visualization and data analysis tools similar to those used by scientists;

(3) by allowing for collaboration and sharing of information across sites; (4) by planning, building, and testing models; and (5) by developing multimedia documents that illustrate student understanding (Novak & Krajcik, 2004). These features expand the range of questions that students can investigate and the multitude and type of phenomena students can experience. Although learners can use a variety of cognitive tools in project-based learning, we place a special focus on the use of learning technologies.

Project-Based Science

In the early 1990s, educators increasingly realized that most students were not motivated to learn science, and that even the best students acquired only a superficial understanding of science. Researchers began to discover that these superficial understandings were caused by a combination of ineffective textbook design and instructional style. Science textbooks covered many topics at a superficial level, focused on technical vocabulary, failed to consider students' prior knowledge, lacked coherent explanations of real-world phenomena, and didn't give students an opportunity to develop their own explanations of phenomena (Kesidou & Roseman, 2002). And although most science teachers have their classes do experiments, most teachers specify the exact sequence of steps that students are supposed to perform – what scientists often refer to as “cookbook” procedures. Following a cookbook recipe doesn't require a deeper understanding of the material, and at best it results in only superficial learning.

In response to these findings, several researchers began to work collaboratively with middle school and high school science teachers to develop project-based instruction in science (Blumenfeld et al., 2000; Krajcik et al., 1994; Krajcik et al., 1998; O'Neill & Polman, 2004; Polman, 1999; Ruopp et al., 1992; Tinker, 1997; William & Linn, 2003). In project-based science (PBS), students engage in real, meaningful problems that are important to them and that

are similar to what scientists do. A project-based science classroom allows students to explore phenomena, investigate questions, discuss their ideas, challenge the ideas of others and try out new ideas. Research shows that PBS has the potential to help all students – regardless of culture, race, or gender – engage in and learn science (Atwater, 1994; Haberman, 1991).

PBS responds to science education recommendations made by national organizations. The National Science Education Standards (National Research Council, 1996) highlight the importance of students doing inquiry to promote personal decision making, participation in societal and cultural affairs, and economic productivity. The AAAS report *Science for all Americans* (AAAS, 1989) calls for students to develop habits of mind such as being aware that there may be more than one good way to interpret a given set of findings, keeping honest and thorough records, and deciding what degree of precision is adequate.

During the 1990s, our group at the University of Michigan, the Center for Highly Interactive Computers in Education (hi-ce) developed strategies for fostering learning in a PBS environment, and designed and developed curriculum materials using the principles of PBS (Blumenfeld et al., 1991; Krajcik et al., 1998; Marx et al., 2004). We worked with high school teachers to develop PBS environments so that different science disciplines (biology, chemistry, and earth science) were integrated into a three-year program (Heubel-Drake et al., 1995). hi-ce also has worked with middle school teachers to transform their teaching (Fishman & Davis, this volume; Novak & Gleason, 2001; Scott, 1994). More recently, we developed curriculum materials as one approach to bring about systemic change in the Detroit Urban Systemic Initiative funded by NSF (Blumenfeld et al., 2000; Marx et al., 2004).

Lessons for Project-Based Learning Environments

Over the last seven years, through our involvement in the Center for Learning

Technologies in Urban Schools (LeTUS) (Blumenfeld et al., 2000; Marx et al., 2004) and the Investigating and Questioning our World through Science and Technology (IQWST) project (Reiser et al., 2003), we worked closely with teachers to design, develop, and test PBS curriculum materials. LeTUS was a collaborative effort among Detroit Public Schools, Chicago Public Schools, Northwestern University, and the University of Michigan to improve middle school science teaching and learning. The collaborative work in LeTUS took as its core challenge the use of inquiry and the infusion of learning technologies to support learning in urban classrooms. IQWST is a joint venture between the University of Michigan and Northwestern University to develop the next generation of middle school curriculum materials. To date, LeTUS materials developed at the University of Michigan have resulted in five different PBS-based curriculum units that teachers can use at the sixth, seventh, or eighth grade levels.¹

While engaged in this work, we have learned many lessons that are relevant to all project-based learning (Blumenfeld et al., 1994; Krajcik et al., 1998; Marx et al., 1997; Tinker & Krajcik, 2001). We've grouped these lessons around the five key features of project-based learning: driving questions, situated inquiry, collaboration, learning technologies, and artifacts.

Feature 1: Driving Questions

The hallmark of project-based learning is a driving question that guides instruction and that learners find meaningful and important (Blumenfeld et al., 1991; Krajcik et al., 2002). A driving question encompasses worthwhile content that is meaningful and anchored in a real-world situation. The driving question serves to organize and drive activities of the project, provides a context in which students can use and explore learning goals and scientific practices, and provides continuity and coherence to the full range of project activities. As students pursue solutions to the driving question, they

develop meaningful understandings of key scientific concepts, principles and practices. A good driving question elicits a desire to learn in students (Edelson, 2001), and it makes students realize that there is an important problem that genuinely needs to be solved (Reiser, 2004). Throughout the project, the teacher calls attention to the driving question to link together the various ideas students explore during the project.

Good driving questions have several features. Driving questions should be (1) *feasible* in that students can design and perform investigations to answer the question; (2) *worthwhile* in that they contain rich science content that aligns with national or district standards and relates to what scientists really do; (3) *contextualized* in that they are real world, nontrivial, and important; (4) *meaningful* in that they are interesting and exciting to learners; (5) *ethical* in that they do no harm to individuals, organisms or the environment (Krajcik et al., 2002).

In PBS, the teacher or curriculum designer select the driving question, or sometimes the students work together with the teacher to select the question (Krajcik et al., 2002; Scardamalia & Bereiter, this volume). Some project-based methods start the process by having students develop their own driving question. This has the advantage that it results in a question that is meaningful to students. However, it is extremely difficult for students to develop driving questions that have all the properties of a good driving question. Our approach has been to design curriculum around a driving question that we select in collaboration with teachers but that allow students either to explore solutions to their own related questions or to engage in a design project to ask related questions in the unit. One of our units is based on the driving question *How Do Machines Help Me Build Big Things?* (*Big Things*) (Rivet & Krajcik, 2004). In *Big Things* students learn about balanced and unbalanced forces and their effect on motion, simple machines and how they work together in complex machines, and the concept of mechanical advantage, and use this understanding to design and

explain a complex machine of their own choosing.

Lesson 1a: Helping Students See the Value of Driving Questions

Often students do not see the value of a driving question. One of the major challenges facing teachers and designers of curriculum materials is to find ways to help students realize the value of the driving questions. One way in which we met this challenge was through the use of *anchoring experiences* (Cognition and Technology Group at Vanderbilt, 1992). Anchoring experiences provide students with common experiences which help them relate to the new ideas explored in the project (Rivet & Krajcik, 2002; Sherwood et al., 1987). Anchoring experiences also present meaningful contexts for the science ideas explored in the project. We use anchoring experiences at the beginning of and throughout a project to show the value of the project's driving question (Cognition and Technology Group at Vanderbilt, 1992; Marx et al., 1997; Rivet & Krajcik, 2004).

In *Can Good Friends Make Me Sick?* (Hug & Krajcik, 2002), an eight-week unit that addresses national standards related to cells, systems, microbiology, and disease, teachers introduce students to the driving question by reading and discussing a story about a young South African boy who contracted AIDS and became an AIDS activist. This story is an anchoring experience that provides a context for discussing how disease relates to them and other middle school children. In a second anchoring experience, students participate in an activity that simulates how an infectious disease might spread through a community. First, they each mix a solution in a test tube. Then, students walk around the class, and when they meet another student, they mix the contents of their test tubes. Some test tubes contain an indicator that reacts with a substance in other test tubes. As students share the content of their test tubes, more and more test tubes change color – simulating the transfer of a communicable disease. This activity provides a common experience

to discuss and relate back to throughout the project (Hug & Krajcik, 2002).

Lesson 1b: Standards Versus In-Depth Examining of Content

A second lesson that we have learned is that many driving questions do not meet important learning goals aligned to national or district standards. In LeTUS, we began by designing curriculum materials using contexts that would engage students and be of interest and value to the community. We selected issues like “What is the quality of air in my community?” and “What is the water like in my river?” Although students find these projects motivating and they met some important learning goals that aligned to national and local standards, starting with these questions did not allow us to systematically meet standards.

In a new materials development effort, *Investigating and Questioning our World through Science and Technology* (IQWST) (Reiser et al., 2003), the IQWST team plans to design, develop, and test the next generation of curriculum materials that teachers and students can use throughout the nation. If these materials are to scale up so that numerous teachers and students use them (Dede, this volume), then one criterion that the materials need to meet is they must help students achieve major learning goals that align with national and district standards. To ensure PBS curriculum aligns with these standards, we plan a three-step process. We start by selecting the national standards students should achieve (Wiggins & McTighe, 1998). For instance, a standard from the National Science Education Standards (NRC, 1996) states that students should know the following:

A substance has characteristic properties, such as density, a boiling point, and solubility, all of which are independent of the amount of the sample. (Content Standard B 5–8: 1A)

But what is it that we expect students to do with this knowledge? To specify what reasoning we expect students to be able

to do with this knowledge, we rewrite the standard in terms of *learning performance* (Perkins et al., 1995). Learning performances restate standards in terms of the cognitive tasks students should perform (Reiser et al., 2003; McNeill & Krajcik, in press). Learning performances reflect the cognitive tasks that we want students to be able to do using scientific knowledge: describe phenomena, use models to explain patterns in data, construct scientific explanations, and test hypotheses (Reiser et al., 2003).

After determining learning performances, we use them as guides for designing the driving question, tasks, and assessments. We believe that this new process will ensure that PBS methods align better with standards. However, we are concerned that when we start with the standards rather than the driving question, it may be hard to find questions that students find meaningful and interesting. In the development of one of the first IQWST units, we started with standardized learning goals related to understanding the nature of chemical reactions and the conservations of mass (McNeill & Krajcik, in press). We had several meetings with teachers to discuss possible driving questions. Some seemed too trivial and did not lead to opportunities for students to explore phenomena. We finally settled on “How do I make new stuff from old stuff?” and we created an anchoring experience of making soap as an example of making new stuff from old stuff.

Feature 2: Situated Inquiry

Throughout the history of science education, national organizations and prominent scientists have argued that science instruction should mirror the scientific process (Hurd, 1970; National Research Council, 1996; Rutherford, 1964; Scardamalia & Bereiter, this volume). Of course, science classrooms are not scientific laboratories. But science classrooms need to be consistent with science. The goal of science is to explain and predict various phenomena – events such as erosion, diseases, rusting,

plant growth, and objects falling to the ground. To answer their questions, scientists take part in scientific inquiry. In scientific inquiry, scientists frame hypotheses that build from theories and previous research; design investigations that allow them to use tools and technologies to gather, analyze, and interpret data; and create explanations of the phenomena. These are *scientific practices*: the multiple ways of knowing and doing that scientists use to study the natural world (National Research Council, 1996). Although scientists do not follow a fixed set of steps that leads them to new scientific understandings, all scientists rely on the use of evidence and theories to explain and predict phenomena that occur in the world.

In PBS classrooms, students explore the driving question using new ideas that they’re learning, and they investigate the driving question over a sustained period of time. This is different from traditional science classrooms, which engage in short-term activities and provide cookbook procedures that are not situated in an inquiry process. In the project “*What is the quality of water in our river?*” (Singer et al., 2000) students conduct different water quality tests, such as pH, turbidity, temperature, and dissolved oxygen to infer water quality. In the project, “*Can Good Friends Make Me Sick?*” students design and conduct investigations to explore various questions regarding the growth of bacteria. By exploring these questions, learners take part in various scientific practices.

Lessons 2 a: Helping Students Design an Investigation

Middle school students find it difficult to engage in the inquiry process, particularly if they’ve had no previous experiences in science (Edelson & Reiser, this volume; Krajcik et al., 1998). To support teachers, our curriculum materials present very thorough details about how to perform a basic investigation related to the driving question. The teacher first models the investigation while asking students to provide suggestions. Next,

the students use these techniques to perform their own investigations while the teacher guides and provides feedback on the process. Hug and Krajcik (2002) explored this strategy in the Communicable Diseases project, in which students explore the growth of bacteria. The teacher begins by asking: "Do I have bacteria on my hands?" and discusses why this makes a good question. The teacher then models how to explore this question by cultivating bacteria, using appropriate experimental techniques such as noncontaminated plate as a control. The next day, after bacteria have grown, the teacher shows students how to count the bacteria colonies and how to use the data to write an evidence-based explanation.

After the teacher models the process, students ask related questions and conduct their own investigations by modifying the procedure modeled by the teacher. Working in teams, students ask questions such as "Does washing my hands make a difference?," "Do different types of soap make a difference?," and "Is there bacteria on the lunch tables after they are cleaned?" The class discusses why these make reasonable and useful questions, encouraging reflection. Next, students design investigations to find solutions to their questions by modifying the procedure the teacher modeled. For instance, if students in a team ask the question, "Does washing my hands make a difference in the amount of bacteria I have on them?," the students need to modify the procedure by designing conditions in which they contaminate the agar plates using nonwashed and washed hands. During the process, teachers give feedback or allow peer feedback to determine if a team's question and a modified procedure is feasible and appropriate. Our curriculum materials support teachers with detailed commentary that provides a rationale for what is occurring as well as how to do it (Davis & Krajcik, 2005).

Lesson 2b: Writing Conclusions and Explanations

After completing investigation procedures and gathering data, the next step is to scaffold

students as they develop their own explanations of the findings. Unfortunately, many studies have found that students have a hard time developing scientific explanations (McNeill & Krajcik, in press; Palincsar, Anderson, & David, 1993). Prior research suggests that it is hard for students to use their explanations to articulate and defend their claims (Sadler, 2004), to understand what counts as evidence, to use appropriate evidence (Sandoval & Reiser, 2004), and to not rely on their personal views (Hogan & Maglienti, 2001). Drawing and justifying conclusions using primary evidence requires sophisticated thinking and much experience, and this type of reasoning has not been required of most students. In fact, even many teachers have trouble engaging in this type of reasoning. Although middle school teachers have experience working with data from highly structured cookbook experiments, they are less likely to have experience using and inferring from real data. As a result, teachers need support in helping students to create explanations and conclusions (Krajcik et al., 1998).

To overcome this challenge, we have become very explicit in the process and reasons behind how to scaffold students as they write explanations (McNeill & Krajcik, in press; Moje et al., 2004). Our scaffolding strategies include making the rationale behind explanations explicit, modeling how to construct explanations, providing students with opportunities to engage in explanation construction, and writing scaffolding comments on students' investigation sheets. We have students use an explanation framework that includes three components: a claim, evidence, and reasoning. The *claim* makes an assertion that addresses the phenomena students are exploring. The *evidence* supports the claim using scientific data that can come from several sources – observations, reading material, archived data, or an investigation that students complete. The *reasoning* provides a justification that links the claim and evidence together, showing why the data count as evidence to support the claim by using the appropriate scientific ideas (McNeill & Krajcik, in press).

Feature 3: Collaborations

Project-based learning provides opportunities for students, teachers, and members of society to collaborate with one another to investigate questions and ideas. The classroom becomes a community of learners (Brown & Campione, 1994). Students collaborate with others in their classroom and with their teacher to ask questions, write explanations, form conclusions, make sense of information, discuss data, and present findings. For example, we ask students to critique and provide feedback to each others' explanations. Collaboration helps students build shared understandings of scientific ideas and of the nature of the discipline as they engage in discourse with their classmates and adults outside the classroom.

Lessons 3 a: Creating a Discourse Community

Students do not naturally collaborate with other students in the classroom (Azmitia, 1996). Teachers need to help students develop skills in collaborating, including turn-taking, listening, and respect for others' opinions (Krajcik et al., 2002). Because students lack skills in collaborating and have had little experience in collaborating, teachers need to build collaborations over the entire school year. Teachers can use a technique in which they first asking students to write down their ideas and then work with a partner to compare their ideas. Written prompts like "My ideas are similar to my partners' ideas in these ways" and "My ideas are different from my partners' ideas in these ways" help students learn to listen to others and compare their ideas to others (Krajcik et al., 2002; compare Andriessen, this volume; Scardamalia & Bereiter, this volume).

Another challenge that teachers face is changing the culture of the classroom from the transmission-and-acquisition style that students expect. Because most students are used to classrooms in which the teacher tells the students the correct answer, they don't take collaborative inquiry seriously at first.

They are conditioned to sit and wait for the teacher to give them the answer, so they don't expend much energy trying to find the answer on their own. Often, teachers too easily fall into this trap and just tell the students the answer, because after all, they will be evaluated on whether or not the students learn the material. To break students out of the habits that they've learned from a lifetime of transmission-and-acquisition instruction, teachers need to work throughout the entire year to get students used to a collaborative way of learning.

Another challenge that we have observed is that teachers will often cut short the time for students to collaborate. Perhaps one reason behind this challenge is that teachers lack appropriate strategies to support students in collaboration. However, another reason might be that teachers don't see collaboration as essential to the meaning making process. This challenge, unfortunately, is much harder to overcome, because it lies at teachers' belief about what fosters understanding.

Feature 4: Using Technology Tools to Support Learning

Technology tools can help transform the classroom into an environment in which learners actively construct knowledge (Linn, 1997; Tinker, 1997; White & Fredrickson, 2000). Edelson (2001) gives three reasons to use technology tools in schools: (1) they align with the practice of science, (2) they can present information in dynamic and interactive formats, and (3) they provide unprecedented opportunities to move teaching away from a transmission-and-acquisition model of instruction.

Students can use learning technologies to access real data on the World Wide Web, to collaborate with others via networks (Stahl et al., this volume; Novak & Krajcik, 2004; Scardamalia & Bereiter, this volume; Schofield, this volume), to gather data, to graph and analyze data (Edelson & Reiser, this volume; Schwartz & Heiser, this volume), to create models (Lehrer &

Schauble, this volume), and to produce multimedia artifacts. Learning technologies allow students to extend what they can do in the classroom, and serve as powerful cognitive tools that help teachers foster inquiry and student learning (Krajcik et al., 2002; Novak & Krajcik, 2004; Linn, 1997; Metcalf-Jackson, Krajcik, & Soloway, 2000).

In the Water Quality project, students use various sensors to gather data about the pH, temperature and turbidity of the river. The students take handheld computers with them to the river, and the data are displayed immediately in a graph. Other sensor devices allow students to collect the data and then view them on computer graphs back in the classrooms. Students use the new ideas they have learned to develop a computer-based model that shows how various factors influence water quality. These technologies help students build connections among the science ideas, forming a deeper and richer understanding.

Lesson 4a: Lack of Computer Access

The “*Can Good Friends Makes Me Sick?*” project utilizes a five-day online activity with *Artemis*² – a digital resource designed for student use (Hoffman et al., 2003). Students used *Artemis* to explore the sources, causes, symptoms and treatments of various communicable diseases. Teachers and researchers agreed that this was a valuable activity because it allowed students to search and synthesize information.

However, teachers seldom used *Artemis* because of challenges in gaining access to the computer lab or because the computers were not configured to access the World Wide Web. Limited access is a major obstacle to the use of learning technologies (Fishman et al., 2004; Schofield, this volume). Because most middle school teachers do not have computers in their rooms, they need to use the school technology laboratory. Unfortunately, computer laboratories are not assigned exclusively to the science class. Teachers would plan to use the

computer room only to find it occupied by another class for the desired day or not available for other reasons. Occasionally, the computer teacher would tell the science teacher that some science technology tools, such as sensors, were not appropriate for the school’s computer lab. At other times, the room would not be configured in a way that was conducive to the use of various software and hardware applications. Still other times, the teacher would prepare the computers for his or her class in advance, only to find that the computers had been changed.

The lesson is that before computers can be fully integrated into classroom instruction, networked computers must be available in every classroom, not only in a dedicated computer lab (Blumenfeld et al., 2000; Fishman et al., 2004; Schofield, 1995, this volume).

Lesson 4b: Time Demand of Using Technology Tools

Because the *Artemis* search task took five days, teachers were hesitant to use it. They recognized its value, but they could not justify the time commitment when faced with other curriculum goals. This lesson corresponds to one of the fundamental tensions facing all constructivist methods – it takes more time to complete a task where students are constructing their own knowledge in meaningful, situated activities.

Lesson 4c: Integrating Learning Technologies into Curriculum Materials

It is important to introduce new learning technologies within the context of an existing curriculum unit. Initially, we did not use PBS ideas to develop curriculum materials for teachers and students, but rather worked with teachers to help them develop understanding for the features of project-based science and modify their curriculum to a project-based format (Krajcik et al., 1994). Teachers and administrators clearly told us that if we wanted teachers with

different experiences, skills, and comfort levels in teaching science to use learning technology and do inquiry, we needed to provide materials that guided teachers in the process. To support teachers with this diversity, we began to develop curriculum materials based on the premises of PBS that incorporated learning technologies (Marx et al., 2004, McNeill & Krajcik, in press; Rivet & Krajcik, 2004).

For example, our *Model-It* software comes packaged with curriculum materials. Students use *Model-It* to build, test, and evaluate qualitative, dynamic models of complex systems such as the human body (Metcalf-Jackson, Krajcik, & Soloway, 2000). The process of model building helps students to understand more deeply the interrelationships among the variables involved within any complex system (Lehrer & Schauble, this volume; Spitulnik et al., 1997; Stratford, Krajcik, & Soloway, 1998).

Software tools like *Model-It* need to be used throughout a project and across several projects, so that students develop deeper understandings of the processes involved in using the tool and of the tool's potential. When students use *Model-It* several times in one project, students come to better understand how to build and test models as well as the importance of model building (Fretz et al., 2002).

Feature 5: Creation of Artifacts

Learning sciences research shows that students learn more effectively when they develop artifacts – external representations of their constructed knowledge. In PBS, these artifacts result from students' investigations into the driving question (Blumenfeld et al., 1991). Students develop physical models and computer models, reports, videotapes, drawings, games, plays, Web sites, and computer programs. To be effective, artifacts need to address the driving question, show the emerging understanding of students, and support students

in developing understanding associated with the learning goals of the project.

PBS focuses on artifact development for several reasons. First, through the development of artifacts, students construct and reconstruct their understanding. As students build and reflect on their artifacts, they actively manipulate science ideas. For instance, when developing explanations, students tie together science principles and concepts to support claims they make about phenomena. Such thinking helps form connections between ideas. This manipulation of ideas generates deeper levels of understanding.

Second, because learning does not occur in linear, discrete steps, assessments should not be constructed around small, discrete bits of information (Pellegrino, Chudowsky, & Glaser, 2001). Learning difficult ideas takes time and often these ideas come together as students work on a task that forces them to synthesize ideas. When students build artifacts throughout a project, they display their learning in a fashion consistent with real-life learning – it unfolds as a continuous process (Krajcik et al., 2002; Scardamalia & Bereiter, this volume). Teachers can use artifacts to see how student understandings develop throughout and across various projects. Artifact development allows teachers to assess for higher level cognitive outcomes such as asking questions, designing investigations, gathering and interpreting data, and creating scientific explanations (Carver, this volume; Atkin & Coffey, 2003; Marx et al., 1997). Third, when students publish what they create, it enhances their understanding. The artifacts that students develop make their understandings visible to others. Because artifacts are concrete and explicit, they allow students to share and have their artifacts reviewed by others – teachers, students, parents, and members of the community (Scardamalia & Bereiter, this volume). Critiquing supports the development of student understanding by providing feedback about what the student knows and doesn't know, permitting learners to reflect on and revise their work.

Lesson 5a: Giving Feedback

Learning sciences research shows that providing feedback on the artifacts that students develop is critical to the learning process (Koedinger & Corbett, this volume; Kolodner, this volume). But unfortunately, teachers rarely give extensive feedback to students. Teachers with large classes and numerous sections do not have enough time in a day or week to give high quality and individual feedback to students. In addition, many middle school science teachers lack knowledge of how to give quality feedback to students.

To help teachers give valuable feedback to students, we provide them with written descriptions of different levels of quality for student performance, to be used for scoring and giving feedback. By providing a common and consistent set of rubrics for PBS tasks such as developing driving questions and providing explanations, teachers learn how to give feedback and students learn how to further their understanding. Teachers have also developed some worthwhile techniques. Many teachers who have large numbers of students per classroom, or who teach the same course to multiple sections, give group feedback. Although not as effective as individual feedback, group feedback does support learning.

Scaling Up

One of the core goals of the Center for Learning Technologies in Urban Schools (LeTUS) (Blumenfeld et al., 2000; Marx et al., 2004) was to work with teachers and administrators to scale the use of project-based science throughout the middle schools in the Detroit Public School System (see Dede, this volume). Throughout the existence of LeTUS, Detroit public schools increasingly adopted the units. In the 1998–1999 school year, our first year of using the projects beyond initial pilot sites, thirteen teachers across ten schools used at least one of the curriculum units. In 2003–2004, sixty-

three teachers in twenty-six schools used and completed the enactment of at least one of the units.

Student performance on curriculum-based posttests, compared to their pretest performance, showed statistically significant gains across all projects in Detroit (Marx et al., 2004). For example, in both the 1998/1999 and the 2000/2001 school year, students using the Air Quality unit showed statistically significant learning gains.³ Three reasons help explain these gains: (1) each year we revised the materials based on analysis of the test scores and observations of classroom enactments, (2) our professional development efforts became more focused (Fishman et al., 2003), and (3) teachers gained experience in using the materials.

In addition to showing learning gains on curriculum-based pre- and posttests, we also have examined student performance on Michigan's state standardized examination – the Michigan Educational Assessment Program. The findings show that students in Detroit who used at least one LeTUS unit did statistically and substantially better on the required state science test than a matched group of students who did not use the LeTUS materials (Geier et al., in press). Moreover, students who used more than one LeTUS unit did significantly better on the state examination than students who used only one LeTUS unit. Our studies of student motivation show that students' attitudes in science remain positive (Blumenfeld et al., this volume; Blumenfeld et al., 2005). This is an important finding, considering that the literature reports that students' attitudes toward science typically decrease substantially during the middle school years (Yager & Penick, 1986).

Findings from other studies that examined student learning in project-based environments also corroborate the findings from our work in LeTUS (Tinker & Krajcik, 2001; Williams & Linn, 2003; Schneider et al., 2001). Taken as a whole, these findings demonstrate that carefully designed, developed and enacted projects result in substantial learning gains.

In order to scale up, we found that we needed to develop what Ball and Cohen (1996) call highly *specified* and *developed* materials. *Specification* refers to the explicitness of curriculum materials. Our materials clearly specify the design principles, intended teaching practices, and desired learning goals, and describe why these are important in enacting PBS. *Development* refers to the provision of resources required to enact the various units, including materials for students and teachers, professional development, and examples of teaching practice.

The drawback to becoming more developed is that the materials are somewhat closed compared to our original vision of PBS. We originally hoped it would be possible for teachers to create projects tailored to their students and community. Although a few teachers can do this, most teachers do not have the time to develop projects; however, highly developed and specified does not mean a return to cookbook experiments or to teacher proof curriculum. Instead, we provide teachers with models of how to enact project-based science and strategies to help learners engage in scientific practices.

Conclusion

Since beginning our efforts in the early 1990s, we have learned how to better design project-based environments. We learned the importance of selecting driving questions that can help students meet important learning goals and the importance of helping students see the value of the driving question. We learned the challenges of using technology and explored various techniques to integrate technology throughout the curriculum. We also learned the importance of supporting teachers in complex instruction by providing them with explicit strategies.

We have learned about how to help teachers do project based science by developing highly developed and highly specified mate-

rials. The materials focus instruction on a driving question that students find meaningful and important, and around which students can develop an understanding of central learning goals. Using these materials, teachers can engage students in scientific investigations, make use of cognitive tools, promote collaboration, and teach them the deeper conceptual understanding that traditional methods of instruction cannot.

Although our research has focused on project-based science, the lessons that we learned apply to any subject area. Projects are widely used in social studies, arts, and English classes. In these subjects, project ideas tend to be passed down by word of mouth, or are developed from scratch by teachers themselves. For the most part these projects are not based in learning sciences research, and researchers have not examined the most effective ways to design these projects. The lessons that we've learned from our research can improve the educational effectiveness of projects in all subjects, because our research is based on core learning sciences principles, and our designs have become progressively better through a process of iterative design experiments (Barab, this volume; Confrey, this volume). As such, they can provide a model for applying project-based methods to classrooms across the curriculum.

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Footnotes

1. You can learn more about and view the materials online at <http://www.hice.org/know>.
2. You can learn more about the technology tools at www.goknow.com/Products/Artemis.
3. Readers can learn more about our assessment procedures in the following manuscripts: Marx et al. (2004), Rivet and Krajcik (2004), and McNeill and Krajcik (in press).

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