14 Project-Based Learning

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Students living in today's 21st-century society will experience dramatic scientific and technological breakthroughs. These students will also face social and global problems that can only be solved with widespread scientific and technological literacy. The science education community has long argued that society needs scientifically literate citizens, and yet research shows that many educational systems throughout the world are failing to graduate such students (OECD, 2007). To prepare children to live in a global 21st-century society, we need to dramatically change how we educate students.

Learning sciences research can show us how to educate students for these 21st-century developments. Drawing on the cognitive sciences and other disciplines, learning scientists are uncovering the cognitive structure of deeper conceptual understanding and discovering principles that govern learning. This research has found that too many schools teach superficial knowledge rather than integrated knowledge that will allow students to draw on their understanding to solve problems, make decisions, and learn new ideas. Drawing on this research, many learning scientists are developing new types of curricula with the goal of increasing students' engagement and helping them develop deeper understanding of important ideas. One such curricular effort is *project-based learning* (Blumenfeld, Fishman, Krajcik, Marx, & Soloway, 2000; Blumenfeld et al., 1991; Krajcik, Blumenfeld, Marx, & Soloway, 1994). Project-based learning allows students to learn by doing, to apply ideas, and to solve problems. In so doing, students engage in real-world activities similar to those of professional scientists.

Project-based learning is a form of situated learning (Greeno & Engeström, Chapter 7, this volume; Lave & Wenger, 1991) and it is based on the constructivist finding that students gain a deeper understanding of material when they actively construct their understandings by working with and using ideas in real-world contexts. Learning sciences research has shown that students can't learn disciplinary content without engaging in disciplinary practices, and they can't learn these practices without learning the content, and this is the basic underlying premise of situated learning. Unfortunately, all too many classrooms separate disciplinary content from practice (Brown, Collins, & Duguid, 1989). To form useable understanding, knowing and doing cannot be separated, but rather must be learned in a combined fashion that allows for problem solving, decision making, explaining real-world phenomena, and connecting new 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. Within the field of science education, this “doing” aligns with scientific and engineering practices (NRC, 2012). A project-based classroom allows students to investigate questions, propose hypotheses and explanations, argue for their ideas, challenge the ideas of others, and try out new ideas. Research has demonstrated that students in project-based learning classrooms attain better learning outcomes than students in traditional classrooms (Geier et al., 2008; Marx et al., 2004; Rivet & Krajcik, 2004; Williams & Linn, 2003).

Project-based learning environments have six key features (Blumenfeld et al., 1991; Krajcik et al., 1994; Krajcik & Czerniak, 2013):

1. They start with a *driving question*, a problem to be solved.
2. They focus on learning goals that students are required to demonstrate mastery on key science standards and assessments.
3. Students explore the driving question *by participating in scientific practices* – 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.
4. 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.
5. While engaged in the practices of science, *students are scaffolded with learning technologies* that help them participate in activities normally beyond their ability.
6. 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 and research that supports 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. During more than 10 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 this 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.

Research Foundations of Project-Based Learning

The roots of project-based learning extend back more than 100 years, to the work of educator and philosopher John Dewey (1959). Dewey argued that the 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. During the past 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 to promote learning in children (Bransford, Brown, & Cocking, 1999; NRC, 2007). Project-based learning is grounded in four major ideas that emerged from the learning sciences: (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 learners actively construct meaning based on their experiences and interactions 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, Chapter 1, this volume). The development of understanding is a continuous, developmental process that requires students to construct and reconstruct what they know from new experiences and ideas and from prior knowledge and experiences (NRC, 2007; Smith, Wiser, Anderson, & Krajcik, 2006). Teachers and materials do not reveal the 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.

Learning deep understanding takes time and often happens when students work on a meaningful task that forces them to synthesize. By focusing on ideas in depth, students learn the connections between key ideas and principles so that they can apply their understanding to as yet unencountered situations, forming what is known as *integrated understanding* (Fortus & Krajcik, 2011).

Situated Learning

Learning sciences research (Nathan & Sawyer, Chapter 2, this volume; NRC, 2007) 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, constructing 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 activity 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 designed to answer a question that they helped to frame and is important to them and their community, they can see how science can be applied to solve important problems. In such environments students develop integrated understanding in which ideas are richly connected to each other (Fortus & Krajcik, 2011).

Compared to traditional classrooms, situated learning generalizes better to a wider range of situations (Kolodner, 2006). 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; Krajcik & Czerniak, 2013) 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 & Kapur, Chapter 6, this volume; Greeno & Engeström, Chapter 7, this volume; Scardamalia & Bereiter, Chapter 20, 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, Marx, Krajcik, & Soloway, 1996). This back-and-forth sharing, using, and debating of ideas helps to create a community of learners that supports students making connection between ideas.

Cognitive Tools

Learning sciences research has demonstrated the importance of *cognitive tools* in learning (Salomon, Perkins, & Globerson, 1991). 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, 2006).

These learning technologies can support students (1) by accessing and collecting a range of scientific data and information; (2) by providing visualization and data analysis tools similar to those scientists use; (3) by allowing for collaboration and sharing of information across sites; (4) by planning, building, and testing models; (5) by developing multimedia documents that illustrate student understanding (Novak & Krajcik, 2004); and (6) by providing opportunities to interact, share, and critique the ideas of others. These features expand the range of questions that students can investigate and the multitude and type of phenomena students can experience.

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 discovered 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; they focused on technical vocabulary; they failed to consider students' prior knowledge; they lacked coherent explanations of real-world phenomena; and they 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 classrooms use materials that specify the exact sequence of steps that students are supposed to perform – often referred 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 instructions in science (Blumenfeld et al., 2000; Krajcik et al., 1998; Krajcik, McNeill, & Reiser, 2008; Polman, 1999; Tinker, 1997; Williams & Linn, 2003). In project-based science (PBS), students engage in real, meaningful problems that are important to them and that mirror what scientists do. A project-based science classroom allows students to explore phenomena, investigate questions, discuss their ideas, engage in scientific practices, challenge the ideas of others, try out new ideas, and construct and revise models. Research shows that PBL has the potential to help all students – regardless of culture, race, or gender – engage in and learn science (Haberman, 1991; Lee & Buxton, 2010; Moje, Collazo, Carrillo, & Marx, 2001).

PBS responds to science education recommendations made by national organizations. The *Framework for K-12 Science Education* (NRC, 2012) highlights the importance of students using various scientific practices, blended with the core ideas of science, to promote personal decision making, participation in societal and cultural affairs, and economic productivity. By engaging in scientific and engineering practices, learners construct meaning by doing science rather than passively taking in information. Learning scientists have demonstrated that children develop deeper understanding by cognitively engaging in the exploration of phenomena (NRC, 2012). Although some individuals can learn about ecosystems by reading about them, most learners need to grow plants, observe animals in ecosystems, and explore how various animals depend on plants and other animals to construct integrated understandings of ecosystems.

Designing project-based learning environments can be a challenge. During the 1990s and 2000s, several scholars developed strategies for fostering learning in a PBS environment and designed and developed curricular materials using the principles of PBS (Blumenfeld et al., 1991; Krajcik et al., 1998; Krajcik et al., 2008; Krajcik, Reiser, Sutherland, & Fortus, 2011; Marx et al., 2004). These researchers 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 (Schneider, Krajcik, Marx, & Soloway, 2001). They also worked with middle school teachers to transform their teaching (Fishman & Davis, 2006; Novak & Gleason, 2001). More recently, these researchers have developed middle school curriculum materials as one approach to bring about widespread change in the teaching and learning of science (Blumenfeld et al., 2000; Krajcik et al., 2008; Marx et al., 2004).

Features of Project-Based Learning Environments

Through our involvement in the Center for Learning Technologies in Urban Schools (LeTUS) (Blumenfeld et al., 2000; Geier et al., 2008; Marx et al., 2004) and the design, development, and testing of Investigating and Questioning our World through Science and Technology (IQWST) materials (Krajcik et al., 2011), 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 scientific inquiry and the infusion of learning technologies to support learning in urban classrooms. IQWST was a joint venture among the University of Michigan, Northwestern University, and the Weizmann Institute of Science to develop the next generation of middle school curriculum materials. While engaged in this work, we expanded our understanding of how to design project-based learning environments that foster integrated understanding and we learned many lessons that are relevant to all project-based learning (Krajcik et al., 1998; Krajcik et al., 2008; Krajcik, Slotta, McNeill, & Reiser, 2008; Tinker & Krajcik, 2001). Based on this research, we have identified six key features of effective project-based learning: driving questions, learning goals, engaging in scientific practices, collaboration, learning technologies, and artifacts.

Feature 1: Driving Questions

The hallmark of project-based learning is a *driving question* that guides instruction. Driving questions should be anchored in a real-world situation that learners find meaningful and important (Blumenfeld et al., 1991; Krajcik & Czerniak, 2013; Krajcik & Mamlok-Naaman, 2006). 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 integrated understandings of core scientific ideas (NRC, 2012). 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 continually refers back 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 questions; (2) *worthwhile* in that they contain rich science content that meets important learning goals 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 & Czerniak, 2013).

In PBL, the teacher or curriculum designer selects the driving question, or sometimes the students work with the teacher to select the question (Krajcik & Czerniak, 2013; Scardamalia & Bereiter, Chapter 20, 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 – particularly meeting worthwhile learning goals. Our approach has been to design curriculum around a driving question that we select in collaboration with teachers but that allows students either to explore solutions to their own related questions or to engage in a design project to ask related questions in the unit. In IQWST (Krajcik et al., 2011), we begin with a driving question but then provide opportunities for students to ask their own question related to the driving question of the project. For instance, in the seventh grade energy unit that focuses on the transfer and transformation of energy, students are introduced to the driving question of the unit, *Why do some things stop while others keep going?* (Fortus, Abdel-Kareem, Jin, Nordine, & Weizman, 2012), through four *anchoring events* in which students experience phenomena related to the transfer and transformation of energy. Anchoring events help students relate to the new ideas explored in the project (Rivet & Krajcik, 2002; Sherwood, Kinzer, Bransford, & Franks, 1987). Anchoring events also present meaningful contexts for the science ideas explored in the project. During the four anchoring events in the energy unit, students observe, describe, and compare and contrast the motion of four objects. One of the objects is a pendulum and another is a spinner top that appears to keep spinning (because the spinning motion results from a battery-driven device). Students use their observations and descriptions of the anchoring events to generate questions. The anchoring events were carefully chosen so that students would be most likely to ask certain questions. For instance: Why does the top keep spinning, but the motion of the pendulum decreases over time? These questions then get posted on the class's Driving Question Board that serves as a road map for teachers and students to check which questions were answered and to add to the explanations of the driving question and student-generated questions as they proceed with the unit. Often these questions become answered as students work through various project tasks.

In *How can you prevent your good friends from getting sick?* (Hug & Krajcik, 2002; Kolodner, Krajcik, Reiser, Edelson, & Starr, 2009–2013) – an eight-week unit that addresses learning goals 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 event that provides a context for discussing how disease relates to them and other middle school children. In a second anchoring event, 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, and as this indicator spreads around, more test tubes change color – simulating the transfer of communicable disease. This activity provides a common experience to discuss and relate back to throughout the project (Hug & Krajcik, 2002) as well as allowing learners to generate meaningful questions related to the driving question and the anchoring event.

Feature 2: Focus on Learning Goals

In most schools, students are required to demonstrate mastery on key science standards and assessments. To ensure PBS curriculum aligns with these standards, we use a three-step process. We start by selecting the important ideas aligned with national or state standards (Krajcik et al., 2008). Project-based environments require considerable curriculum time to enable students to focus on ideas, revisit those ideas, collaborate with peers, explore phenomena, and develop integrated understanding. As such, teachers must feel confident that the investment of time is warranted in terms of meeting these districts' and states' mandated learning goals.

In developing the "Investigating and Questioning Our World through Science and Technology" (IQWST) middle school curriculum, we used a learning goals-driven process to ensure that materials would meet key learning goals. The process consisted of three major steps: (a) select core ideas, (b) unpack the ideas, and (c) develop learning performances that express the desired cognitive tasks (Krajcik et al., 2008). To select core ideas, we used two main criteria. First, the core idea must have explanatory power in that it is necessary for understanding a variety of phenomena. Second, the core idea must be necessary for future learning in the sense that it is generative or is needed to understand related topics. The particle nature of matter is one such core idea. The particle nature of matter can be used to explain a host of phenomena from how water evaporates to why mass is conserved during chemical reactions. The *Framework for K-12 Science Education* also identified the particle nature of matter as a Core Idea of Science (2012). The particle nature of matter is also a core idea because it is necessary for understanding many advanced topics, like photosynthesis and respiration.

Once a core idea is selected, it is important for curriculum developers to unpack the idea. The process of unpacking involves decomposing the core idea into its component parts and concepts, and then expanding and identifying those concepts. Unpacking allows designers to develop a much deeper understanding of the core idea and of the essential aspects of that idea that need to be considered in curriculum design (Krajcik et al., 2008). (See Krajcik et al., 2008, for an example of unpacking.) And of course, these component concepts must be suitable for the age and grade level of the students.

To specify what reasoning we expect students to be able to do with core ideas, we write learning goals in terms of *learning performances* (Perkins, Crismond, Simmons, & Unger, 1995). Learning performances blend core ideas with scientific practices (Krajcik et al., 2008). Learning performances reflect the professional disciplinary practices of working scientists: describe phenomena, use models to explain patterns in data, construct scientific explanations, and test hypotheses (Krajcik et al., 2008). Table 14.1 shows an example of forming a learning performance.

Learning performances can then be used as guides for designing the driving question, tasks, and assessments. The focus on learning performances is consistent with our perspective on situated learning: learning performances blend the knowing and the doing.

The goal of this process is to ensure that PBS materials meet important institutionally mandated standards while also supporting students in

Table 14.1. *Developing learning performances*

Core Idea Blended with a Practice to Develop a Learning Performance		
All substances are made from some 100 different types of atoms, which combine with one another in various ways. Atoms form molecules that range in size from two to thousands of atoms. Pure substances are made from a single type of atom or molecule; each pure substance has characteristic physical and chemical properties ... that can be used to identify it. Gases and liquids are made of molecules or inert atoms that are moving about relative to each other. In a liquid, the molecules are constantly in contact with others; in a gas, they are widely spaced except when they happen to collide. In a solid, atoms are closely spaced and may vibrate in position but do not change relative locations (NRC, 2012).	Developing and using models	Constructing and communicating models to predict and explain the motion of molecules in various phases and during phase change.

achieving deeper and more integrated understanding. However, one risk is that when one begins with the standards rather than the driving question, it may be hard to find questions that the students find meaningful and interesting. In the development of one of the first IQWST units, we started with learning goals related to understanding the nature of chemical reactions and the conservations of mass (Krajcik, McNeill, & Reiser, 2008). 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 event of making soap as an example of making new stuff from old stuff.

Feature 3: Engaging in Scientific Practices

Beginning with the U.S. science education reforms of the 1960s, policy makers and prominent scientists have argued that science instruction should mirror what scientists do (Hurd, 1970; NRC, 1996, 2007, 2012; Rutherford, 1964). 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 various

Table 14.2. *Scientific and engineering practices (NRC, 2012)*

- Asking questions (for science) and defining problems (for engineering)
- Developing and using models
- Planning and carrying out investigations
- Analyzing and interpreting data
- Using mathematical and computational thinking
- Constructing explanations (for science) and designing solutions (for engineering)
- Engaging in argument from evidence
- Obtaining, evaluating, and communicating information

scientific practices (see Table 14.2) – asking questions, designing and performing investigations, constructing models, using evidence, and developing explanations (NRC, 2012). 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, models, and theories to explain and predict phenomena that occur in the world. Science is truly a nonlinear endeavor. For instance, each component provides feedback that may lead to a different practice. For example, finding information about a topic might lead students to refine their questions or to redesign their investigation, and data analysis might result in revising the experimental design.

In PBS classrooms, students explore the driving questions 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 are characterized by short-term activities and cookbook procedures. For example, in the project "What is the quality of water in our river?" (Singer, Marx, Krajcik, & Chambers, 2000), students conduct different water quality tests, such as pH, turbidity, temperature, and dissolved oxygen to infer water quality. In the project "How can I smell things from a distance?" (Merritt, Sutherland, Shwartz, Van de Kerkhof, & Krajcik, 2011), students design and conduct investigations to explore various questions about how odors can travel across a room. By exploring these questions, learners take part in a range of scientific practices, including designing and performing investigation, refining questions, constructing and revising models, and developing explanations.

Middle school students find it difficult to engage in various scientific practices, particularly if they've had no previous experiences in science (Edelson & Reiser, 2006; Krajcik et al., 1998). To support teachers, the IQWST materials present very thorough detailed commentary on how to support students in various scientific practices – particularly modeling (Krajcik & Merritt, 2012) and scientific explanation (McNeill & Krajcik, 2012). Unfortunately, many studies have found that students have a hard time developing scientific explanations (McNeill & Krajcik, 2008). 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 science classes. Because many middle school teachers have experienced 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, 2008; 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 (also see Andriessen & Baker, Chapter 22, this volume). 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, 2012). This framework provides a structure to support both students and teachers in constructing explanations in science classrooms.

Feature 4: 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) as students 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 on each others' explanations. Collaborations helps students build shared understandings of scientific ideas and of the nature of the discipline as they engage in discourse with their classmates and with adults outside the classroom.

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. 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 ask 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 those of others (Krajcik & Czerniak, 2013; Scardamalia & Bereiter, Chapter 20, this volume).

Feature 5: Using Technology Tools to Support Learning

Technology tools can serve as learning tools to help transform the classroom into an environment in which learners actively construct knowledge (Linn, 1997; Tinker, 1997). 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 (Novak & Krajcik, 2004; Scardamalia & Bereiter, Chapter 20, this volume; Stahl, Koschmann, & Suthers, Chapter 24, this volume), to gather data, to graph and analyze data (Edelson & Reiser, 2006), to create models (Lehrer & Schauble, 2006), to share and find information, 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 (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. These activities assist students in analyzing and interpreting data and computation reasoning practices. 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.

Mobile technologies have changed lifestyles, and the potential and demand for using them in classroom settings have increased greatly over the past few years (Sharples & Pea, Chapter 25, this volume). Tinker and Krajcik (2001), more than a decade ago, underlined that mobile technologies would become inexpensive so that schools could afford one for each student; today this claim is supported by the work of Norris and Soloway (2009), who encourage the use of mobile devices for every student. Researchers at the University of Michigan (Cahill, Kuhn, Schmoll, Pompe, & Quintana, 2010) have designed

Figure 14.1. *An augmented reality learning environment.*

a mobile tool, Zydeco, that supports students in three important scientific practices: specifying and refining the questions; collecting, sharing, and organizing data; and constructing scientific explanations.

Technologies also hold other advantages for students. Shin and her colleagues have designed augmented reality (AR) to support student understanding of core science ideas in chemistry by linking micro and macro worlds in a mobile learning environment. In this investigation, while students observe macro-world phenomena, the learning tool using AR presents a virtual molecular-level representation showing the movements of molecules to support students' conceptual understanding in a meaningful way. This learning tool has integrated handheld devices (e.g., iPad with camera), and various technologies (e.g., simulation, video, augmented reality) for students to develop understanding of underlying models while they conduct lab experiment in a real classroom. Figure 14.1 shows an example of an augmented reality environment that demonstrates the relationship between gas and volume.

Recently, researchers have designed technology-enhanced materials to create individualized, customized learning environments that provide equal learning opportunities for all students by accommodating the range of ways that diverse students develop their understanding (Choi & Shin, 2009; Rose, Meyer, & Hitchcock, 2005, Shin, Sutherland, & McCall, 2011). The key principle is that given the same learning goals, different students learn in different ways for perceiving and comprehending new information and representing their understanding in a learning environment (Bransford et al., 1999).

Given this perspective, educational materials with multiple representations (e.g., text, picture, video, animation/simulation, audio, augmented reality), various difficulty levels of learning tasks, and different levels of support are necessary to appeal to the interests and meet the needs of individual learners (Rose et al., 2005). For example, Krajcik and Shin, working with information and technology developers in Korea (VisangESL inc.), have designed individualized learning environments using Universal Design for Learning (UDL) principles and Learning Progressions (LP) based on the "How can I smell things from a distance?" unit (Merritt et al., 2011). The materials were adapted from development work initially designed using UDL principles (http://udl-toolkit.cast.org/home). Learning progression (LP) supports the organization and alignment of the science content, instruction, and assessment strategies to provide students with the opportunity to develop better understanding. A learning progression (LP) describes the "successively more sophisticated ways of thinking about a topic that can follow one another as children learn about and investigate a topic over a broad span of time" (Duschl, Schweingruber, & Shouse, 2007, p. 219). We embedded assessment items associated with various levels of the LP into learning tasks to diagnose the level of individual performances before instruction (Shin & Stevens, 2012). An individualized environment is presented to guide each student based on his or her test scores by providing level-appropriate instruction. Figure 14.2 shows an individual path that a student might take in using the materials. The black "flags" that appear in the upper right corners of four of the images indicate a suggested learning path based on a student's test score. We believe that such instructional materials can maximize individualized, independent learning, which can lead to more meaningful learning.

Feature 6: 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, videos that document their investigations, games, plays, Web sites, and computer programs. To be effective, artifacts need to address the driving question, support students in developing understanding associated with the learning goals of the project, and demonstrate student understanding of 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. 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). Teachers can use

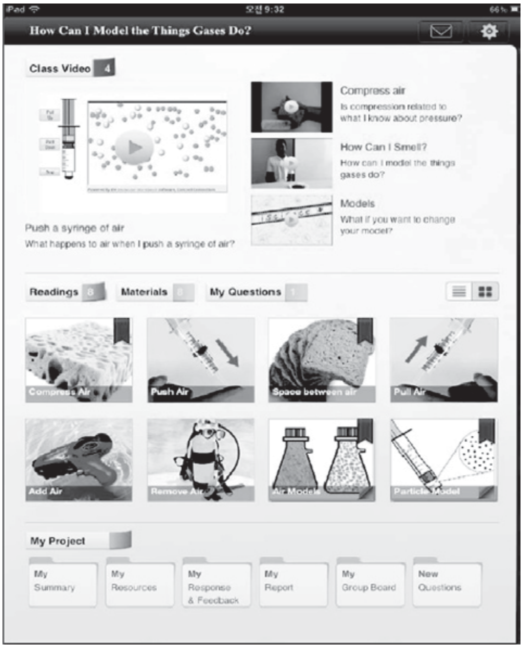

Figure 14.2. *Individualized learning environment (ILE): Touch pad device. The black "flags" in the upper right corners of four of the images in the bottom half of Figure 14.2 illustrate an individual learning path that a student can follow.*

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 (Atkin & Coffey, 2003; Carver, 2006). Third, when students publish or make publically available what they create, it enhances their motivation to create a product that others will understand. 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, Chapter 20, 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.

Learning sciences research shows that providing feedback is critical to the learning process (McNeill & Krajcik, 2009; Pellegrino, Chudowsky, & Glaser, 2001). 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, McNeill and Krajcik (2011) provided 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.

Conclusion

Research over the past two decades has shown us how to better design project-based environments. In this chapter, we have emphasized the importance of selecting driving questions that can help students meet important learning goals, help students see the value of the driving questions, and engage students in scientific practices. We have emphasized the importance of developing learning goals that focus on learning performance by blending core ideas and scientific practices. We have described some of the challenges of using technology and explored various techniques to integrate technology throughout the curriculum. We have emphasized the need to support teachers in complex instruction by providing them with explicit strategies.

The research with PBL shows the importance of helping teachers by developing highly developed and highly specified materials that focus instruction on driving questions 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 understating that traditional methods of instruction cannot.

Although the bulk of this chapter has focused on project-based science, the lessons 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 findings that we summarize in this chapter can improve the educational effectiveness of projects in all subjects, because this research is based on core learning sciences principles and these designs have become progressively better through a process of iterative design experiments. As such, they can provide a model for applying project-based methods to classrooms across the curriculum.

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