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Doing With Understanding: Lessons From Research on Problem- and Project-Based Learning

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A major hurdle in implementing project-based curricula is that they require simultaneous changes in curriculum, instruction, and assessment practices—changes that are often foreign to the students as well as the teachers. In this article, we share an approach to designing, implementing, and evaluating problem- and project-based curricula that has emerged from a long-term collaboration with teachers. Collectively, we have identified 4 design principles that appear to be especially important: (a) defining learning-appropriate goals that lead to deep understanding; (b) providing scaffolds such as "embedded teaching," "teaching tools," sets of "contrasting cases," and beginning with problem-based learning activities before initiating projects; (c) ensuring multiple opportunities for formative self-assessment and revision; and (d) developing social structures that promote participation and a sense of agency. We first discuss these principles individually and then describe how they have been incorporated into a single project. Finally, we discuss research findings that show positive effects on student learning and that show students' reflections on their year as 5th graders were strongly influenced by their experiences in problem- and project-based activities that followed the design principles.

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This special issue on problem- and project-based learning environments is timely. There is renewed enthusiasm for approaches to instruction that emphasize the connection of knowledge to the contexts of its application. Recommendations by nationally commissioned educational boards and teacher-directed publications reflect this enthusiasm (American Association for the Advancement of Science [AAAS], 1989; National Council of Teachers of Mathematics [NCTM], 1989; Resnick & Klopfer, 1989). As researchers engaged in some of this work ourselves, we have had the opportunity to experience both the potential pitfalls and promises that accompany this family of approaches. Our goal is to share some lessons learned from our research and development efforts.

The history of the idea of "learning by doing" makes clear the need for informed discussions about problem- and project-based approaches. Projects, as a means to make schooling more useful and readily applied to the world, first became popular in the early part of the century within the United States. The term *project* represented a broad class of learning experiences. For example, in early works one sees the label "project" applied to activities as diverse as making a dress, watching a spider spin a web, writing a letter, or learning the "why and wherefore of the World's Series" (Hotchkiss, 1924, p. 111; McMurray, 1920). The unifying idea was that students learn best when "wholeheartedness of purpose is present" (Kilpatrick, 1918). Enthusiasm and belief in the efficacy of the project approach for school-aged children, however, waxed and waned. In the end, only a minority of teachers consistently adopted such innovative practice (Cuban, 1984; Elmore, 1996).

Various explanations have been given for the fact that project-based learning took hold in a small number of public school classrooms: inadequate material resources, little time to create new curricula, large class sizes, and over-controlling administrative structures that prevented teachers from having the autonomy necessary to implement progressive approaches. Also cited were growing incompatibilities between progressive approaches and college entrance requirements (Tyack & Cuban, 1995). Critics of midcentury attempts to renew interest in project-based approaches further dispelled the public's enthusiasm by arguing that project-based learning often leads to doing for the sake of doing. Given that few reformers gave teachers the type of support required to make such significant change in practice, this critique may have had some truth to it.

As a nation, we are in danger of once again failing to realize the educational potential of these reemerging approaches. If curriculum changes are not made carefully with adequate planning and support, we risk a political backlash that favors back-to-basics and rote learning over authentic inquiry. Although there is evidence that problem-and project-based learning can be successful (e.g., Cognition and Technology Group at Vanderbilt [CTGV], 1994, 1997; Collins, Hawkins, & Carver, 1991; Hmelo, 1994; Schauble, Glaser, Duschl, Schulze, & John, 1995;

Williams, 1992), our experiences in schools suggest that the repetition of past errors is a distinct possibility.

Over the past few years, teachers and researchers working at the Learning Technology Center at Vanderbilt University have been intimately involved in planning and evaluating problem-and project-based approaches to instruction. In this work, we first engage students in problem-based learning by providing them with opportunities to tackle complex problems situated in video-based stories. We then have students complete thematically related projects that result in a tangible, real world outcome. In this article, we focus on four principles of design that, in our experience, can lead to doing with understanding rather than doing for the sake of doing. These principles are:

1. Learning-appropriate goals,
2. Scaffolds that support both student and teacher learning,
3. Frequent opportunities for formative self-assessment and revision, and
4. Social organizations that promote participation and result in a sense of agency.

These principles mutually support one another toward two ends. One end is the acquisition of content and skills. The other end is to help students become aware of their learning activities so they may take on more responsibility and ownership of their learning. This awareness includes many aspects of what has been characterized under the umbrella term *metacognition*—knowing the goal of their learning, self-assessing how well they are doing with respect to that goal, understanding that revision is a natural component of achieving a learning goal, and recognizing the value of scaffolds, resources, and social structures that encourage and support revision. We begin by discussing the rationale behind each of the four principles separately, and we draw on several teaching experiments that help clarify their importance. We then illustrate how they were interwoven into a single project to create an educational experience that fostered doing with understanding. In this project, students have the opportunity to learn how basic concepts of geometry are related to architecture in the context of designing playgrounds and playhouses. We share examples of student work from this project as well as analyses that examine pretest to posttest changes across classrooms and as a function of prior achievement levels.

DESIGN PRINCIPLES TO SUPPORT PROBLEM- AND PROJECT-BASED LEARNING

Learning-Appropriate Goals

Project-based learning experiences are frequently organized around a driving question (Blumenfeld et al., 1991). Too frequently, however, the question that drives a project is not crafted to make connections between activities and the underlying conceptual knowledge that one might hope to foster. Although the opportunity for deep learning is there, it often does not occur because of the tendency in project-based approaches to get caught up in the action without appropriate reflection (see Blumenfeld et al., 1991; Schauble et al., 1995). In such cases, the "doing" of an activity takes precedent over "doing with understanding."

An example of the need for a well-crafted, driving question comes from projects in model rocketry. Petrosino and his colleagues (Lamon et al., 1996; Petrosino, 1995) have worked at a number of Nashville sites on a "Mission to Mars" curriculum that includes a component in which students build and launch model rockets. Thousands of classrooms throughout the country engage in similar types of activities. At the Nashville sites, the opportunities to build and launch rockets have been extremely popular for students, teachers, and parents. Launchings frequently attract press attention with footage shown on local news programs. There are many reasons to proclaim such projects a success.

However, what do students actually learn from their experiences? Petrosino (1998) found out that many sixth-grade students who completed the traditional rocket project learned relatively little from the hands-on activity of simply making and launching their rockets. They did not, for example, understand what made a better or worse rocket, and they did not understand how to evaluate the effectiveness of their rockets in any systematic way. One reason for this may be that the students did not have a driving question that could foster focussed inquiry. For example, when students were asked what they thought about the purpose of the activity, a typical response was "You know, to build them and see how high they will go." In response to a question about measuring how high things go, a common response was "You know, look at it go up and see how high it goes."

Petrosino (1998) explored whether it was possible to deepen the students' understanding without dampening their enthusiasm; could the students learn about experimentation and measurement if they had an appropriate "driving question" behind the rocket project? To examine this question, Petrosino added a learning-appropriate goal to the standard rocket project that motivated the use of scientific methods. In the new version, sixth-grade students submitted design plans to National Aeronautics and Space Administration for a rocket kit that would be used by many classes (Petrosino, 1998). The "Request for Design Plans" included the following specifications:

> We are specifically interested in three questions. First, will our rockets go higher if we sand and paint them or leave them unfinished? While it would be much cheaper for us not to paint and sand our rockets, we want to maximize the height our rockets reach. Second, will the number of fins have any effect on the height of the rockets; primarily 3 vs. 4 fins? Again, there are economic considerations involved. Third, does

> the type of nose cone have an effect on the height of the model rocket? We have rounded and pointed cones. (p. 240)

Exit interviews with students indicated that they understood the design goals, and they learned important skills like controlled experimentation and methods of measurement that would help achieve these goals. The following excerpt is representative and provides a strong contrast to the quote presented earlier in which the students explain the point of launching the rockets:

> Q: So, why were you doing the model rocket activity?
> A: We were doing it for NASA and they asked us to see which rocket or which kind of rocket we could build to go in a straight path. We had to build the rocket and see which will go higher, the one with four fins or the one with three fins. Should it be painted or not painted. Should the nose cone be rounded or pointed.
> Q: How would you measure it?
> A: You would get 150 meters away from the object. You set the finder of the altimeter to zero. Once the rocket launches you wait until it gets to its highest point and shoot and let go of the trigger. You then bring the altimeter slowly down and get an accurate number for the height.

Not only did students understand what they were trying to learn, but this knowledge appeared to help them direct their learning. One classroom teacher, for example, was impressed by the students' increased ability to generate their own questions to guide their scientific inquiry. "That was one thing I was very excited about: that they didn't have answers to all their questions; but they had better questions. I was impressed to see that, and felt glad to be a part of that process."

In terms of learning scientific methods, compared to students from the previous years, the inquiry goals led students to reflect on the rocket launches as sources of data for deciding on the best design features. Consequently, the students learned how to measure the height of a rocket launch, recorded results from each launch, noticed and recorded sources of variance in their measurements (e.g., a windy day), and debated what features should be experimentally manipulated in each subsequent rocket trial. Rather than develop those data here (see Petrosino, 1998), it may be enough to describe an anecdote from Petrosino's study. His "learning-appropriate goal" students saw children at the far end of the launching field who were igniting their own rockets. These other students were from a class that had not received the "Request for Design Plans." The "learning-appropriate" students spontaneously ran to the other students and asked, somewhat mystified: "Don't you want to know how high your rockets are going?" The students from the other class were simply launching their rockets. The goals of the "Request for Design Plans" helped Petrosino's students to realize there were things that were important to find out, and they were willing to learn how to achieve that knowledge. Moreover, the students evidently thought the knowledge was worthwhile because they spontaneously started to teach the other students how to measure the altitudes reached by the rockets.

Scaffolds That Support Both Student and Teacher Learning

The modified rocket project is an example of a design project. We are not alone in recognizing the potential of design activities for engaging students in learning about experimental methods and domain knowledge. For example, Schauble et al. (1995) were engaged in teaching experiments in which children designed vessels that could carry construction materials up a river. Whereas this work has provided positive evidence for the usefulness of extended design work, it has also yielded important insights about the difficulty of implementing such instruction in the classroom. Specifically, Schauble et al. identified a number of tradeoffs that the teachers found difficult to negotiate. These included the balance between having students carry out design activities on the one hand and reflect on this work on the other, how to integrate students' real-world knowledge without letting it have too much influence over lesson plans, and how to maintain student engagement over an extended period of time in a way that pushes principled understanding rather than simply appealing to students' desire to tinker with their projects. We too have struggled with these tradeoffs. Learning in complex environments can be difficult, and this complexity can increase the likelihood of simply following procedures rather than doing with understanding.

The first principle, providing learning-appropriate goals, helps create a need for students to understand the how and why of a project. We have found, however, that it is often necessary to provide additional scaffolds to support the teaching and learning process. Scaffolding was originally defined as a "process that helps a child or a novice to solve a problem, carry out a task, or achieve a goal which would be beyond his unassisted efforts" (Wood, Bruner, & Ross, 1976, p. 90). Further distinctions between kinds of scaffolds have been made. Collins, Brown, and Newman (1989), for example, defined three types: (a) those that function to communicate process, (b) those that provide coaching, and (c) those that elicit articulation (for distinctions between types of software-realized scaffolding, see Hmelo & Guzdial, 1996). In our work, we provide scaffolds that fall into each of these categories. In particular, we design them to help students understand the relevance of particular concepts to activities in the world and to support inquiry skills, deep understanding, and the reflection on one's idea in relation to others'. By inquiry skills, we mean the abilities of students to research topics to advance their understanding and to collaborate and communicate with others in the furtherance of this goal. Deep understanding of subject matter includes the ability to explain phenomena (e.g., in model-based terms) rather than simply describe various procedural activities that are part of one's project. Next, we describe two types of scaffolds we have employed: starting with problems and using contrasting cases.

Problem-Based Learning As a Scaffold for Projects

One of the most important ways to scaffold open-ended projects is to help students and teachers continually reflect on how and why their current activities are relevant to the overall goals (the big picture) of the project. One of our main approaches to scaffolding children's efforts with the open-endedness of projects has been to begin with problem-based learning and then to proceed to projects. The problem-based learning provides a big picture without entailing the ill-defined complexity often associated with open-ended projects. Our version of problem-based learning (see CTGV, 1992; Williams, 1992) involves the use of authentic but simulated problems that students and teachers can explore collaboratively. The Learning Technology Center's *Jasper Series*, *Scientists in Action Series*, and *Young Children Literacy Series* are examples of problem-based learning environments. Each of these series consists of a number of video-based or animated anchor stories. The stories follow a narrative structure with one exception: They do not end with a conclusion but rather with a challenge for the students who are watching. The information needed to meet the challenge has been included in the story. In contrast, our project-based learning experiences are typically centered in everyday settings with tangible outcomes. So, for example, we treat actively monitoring a river as project based whereas working with a simulated, river emergency is problem based. Additional examples include constructing a playhouse for a community center versus designing in a simulated context and actively planning and carrying out a fun fair at school versus planning for an imaginary fair.

A relevant problem-based challenge can serve as a scaffold for more open-ended, subsequent projects for many reasons. A relatively circumscribed problem can support the initial development of vocabulary and concepts, and video-based problems, in particular, can present role models of students carrying out complicated work. Moreover, we can easily embed scaffolds in the problem materials that support students as they grapple with the complexity of thought needed for problem-based and future project-based learning. For example, video formats support the development of a student's mental model of the problem-solving situation. Furthermore, video-based problems can incorporate embedded teaching scenes that seed important concepts, solution strategies, and focal points for classroom discussion. Within these scenes, the content is usually delivered within the context of a conversation between characters in the story. We have also developed adjunct teaching tools that can be used in a just-in-time fashion to support students when they bump up against a difficult issue when solving the problem (CTGV, 1997). These teaching tools take on a variety of forms including simulation environments and text-based resources. We describe some of these tools in the context of Special Multimedia Arenas for Refining Thinking (SMART) Blueprint discussed later. For now, what is important is that these tools support the problem-based learning, whereas in turn, they serve indirectly as scaffolds for subsequent project-based learning.

Our work suggests that there are strong advantages to pairing problem- and project-based activities. For example, by beginning with a simulated problem, students develop a level of shared knowledge and skill that prepares them to undertake actual projects. By following the problem with a project, students are likely to develop more flexible levels of skills and understanding. In addition, if students know they will be completing real projects in their community, they are motivated to learn. Students view the problem-based learning as preparing them for "the real thing". In the next paragraphs, we fill out some of these ideas by presenting two successful examples: one that focusses on benefits to students and one that focusses on benefits to teachers.

Benefits for students. A study conducted with 62 sixth-grade students by Moore, Sherwood, Bateman, Bransford, and Goldman (1996) illustrates the value of engaging in problem-based learning prior to work on actual projects. In both the control and experimental conditions, the students were teamed into 8 groups of 3 to 4 students. Their task was to design a business plan for a booth at their school carnival. Moore et al. knew from previous work that this was a project that excited students, especially when they knew that successfully designed and defended plans would actually be carried out in their schools. The difference between the conditions was that the experimental students completed a simulated problem-based, business-planning activity prior to designing the booth for their own school. The control group began their design process without the benefit of an initial simulated task.

The problem-based activity used for the experimental group involved the *Jasper* adventure *The Big Splash*. In this adventure, students are introduced to a young man named Chris. Chris's school is planning for a fun fair intended to raise money to buy a school video camera. Chris has an idea: He will make a dunking machine booth in which students can buy tickets for a chance to dunk a teacher. His principal likes the idea, but she also wants proof that the booth will make a profit. Specifically, she wants an itemized list of expenses, an estimate of revenue, and a complete plan for how the logistics will be handled. In the remainder of the story, we see Chris doing an extensive amount of research as he prepares to make his business plan. He collects data from fellow students to determine the best ticket price and to estimate his revenue, he visits a pool store to find out about the costs of renting a pool, and he investigates several options for filling the pool that differ in terms of cost and speed. Based on the information Chris gathers, the students in the classroom have to select the relevant information, formulate subproblems, and write a feasible business plan that demonstrates the logic of their thinking.

In the experiment by Moore et al. (1996), students in the experimental group spent three, 1 hr class periods solving *The Big Splash*. Even though carried out over a relatively short time, the experience had a powerful effect on the students' subsequent abilities to craft plans for a booth of their choice at their actual school. For example, two judges, blind to condition, looked at the written plans of both the experimental and control groups and rank ordered them in terms of quality. Results are illustrated in Figure 1. Plans written by the students who first completed problem-based learning were generally of a much higher quality than were plans from the project-based-only group.

Additional analyses by Moore et al. (1996) suggest that the problem-based experience helped students pay attention to important considerations and address alternatives with more than just opinion. For example, the students in the experimental condition actually polled students at their school to get an estimate of their revenue for different booth alternatives. Not only did the initial problem-based experience help the students navigate through the many possibilities afforded by an open-ended context, it also helped them approach those possibilities mathematically. This is important in that one goal of projects should be for students to learn, and be able to use, formal knowledge in an authentic and complex setting. A simple evaluation helps make the point. The students were told that their plans would be evaluated along four criteria: expenses, ticket price, total revenue, and profit. For each element, plans were assigned a score indicating level of mathematizing. A 0 score indicated that a plan did not mention an element, a 1 meant it mentioned an element but did not attempt to mathematize it, a 2 meant it mathematized the element, and a 3 meant it successfully mathematized the element to achieve a solution. A primary rater coded all presentations and a secondary rater coded a sample of 25% of the presentations with 90% agreement. The primary rater's codings were used. Figure 2 shows that beginning with the problem-based experience led to superior mathematizing on the subsequent project for each of the four key elements. It is interesting to note that all 16 groups mentioned all of the problem elements except for profit (50% overlooked profit in the project-only condition and 25% in the *Jasper*-plus-project condition). Thus, even though the project-only groups attended to the stated criteria for plan evaluation, they still did not mathematize their work. Perhaps, if they had done a suitable problem-based activity first, they would have learned that mathematics was an important part of business planning.

Benefits for teachers. We have also experimented with using preliminary problem-based learning in the context of projects that involve monitoring rivers for pollution. In a recent study, we found that fifth-grade students who completed a common unit on river pollution enjoyed the experience and felt that they had "learned a lot." Nevertheless, a closer examination of their learning revealed that it was disappointingly low. For example, nearly all students understood that one way to monitor river quality is to sample the kinds of organisms that live in the water—especially macroinvertebrates. Nevertheless, almost none of them developed a clear understanding of macroinvertebrates as an indicator species; many believed that healthy rivers contain no macroinvertebrates—rivers should be like

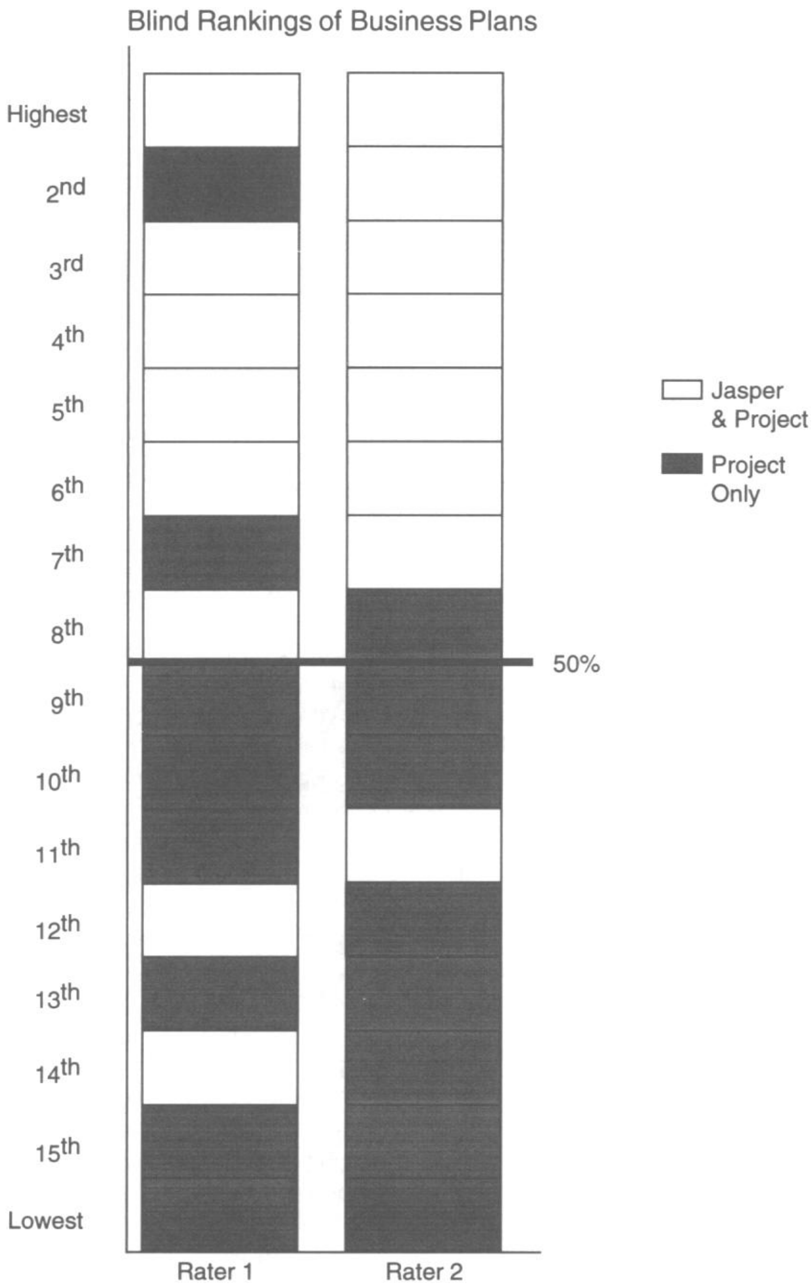

FIGURE 1 Rank order of business plans created by students in a project-only condition and in a problem-plus-project condition.

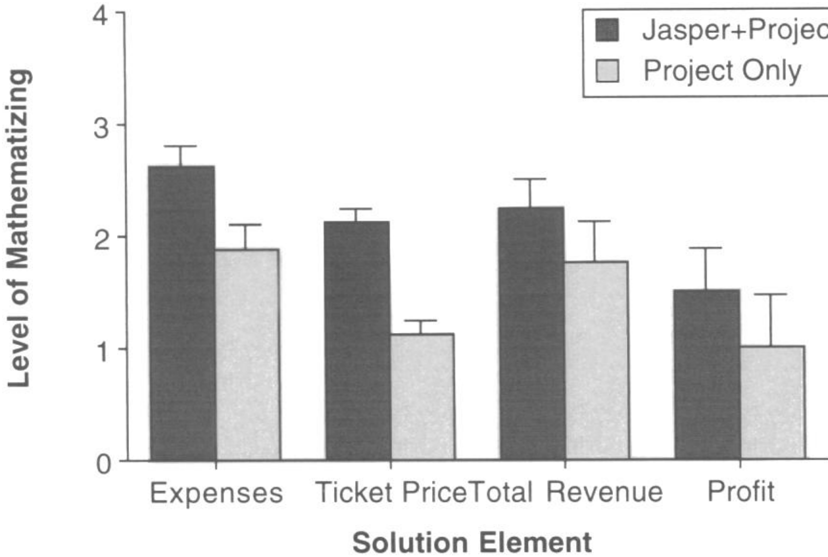

FIGURE 2 The level of mathematizing by students in the project-only condition and in the problem-plus-project condition.

swimming pools. Moreover, the students did not understand the links between pollutants, bacteria, macroinvertebrates, and dissolved oxygen. When given an assessment that required an understanding of these interdependencies, the students in the traditional river curriculum showed no gains from pretest to posttest.

To look at how river monitoring projects can be affected by prior problem-based learning opportunities, we worked with fifth-grade teachers who had conducted water-monitoring projects the previous year. The teachers agreed to change their instruction to first include a problem-based component. This component was anchored around the *Scientist in Action* adventure *Mystery of Stone's River* and supplemented by the Special Multimedia Arenas for Refining Thinking (SMART) assessment model that provided multiple opportunities for formative assessment. We discuss SMART in more detail in the section on formative assessment.

Data indicate that students who experienced the problem-to-project approach to river monitoring developed important insights about the interdependence of ecosystems and the effects of pollution on this interdependence. Rather than relay these data here (see Vye et al., 1997), we consider the comments from teachers who were asked to compare their assessments of student learning in the problem-to-project sequence with assessments of what had been learned the previous year without any problem-based preparation:

Teacher 1: The SMART River curriculum is very different [from the one used previously] and the difference showed when students went to the river. The focus in the SMART curriculum was on a balanced ecosystem. When the students went to the river, they looked for that balance. There was no focus in the other curriculum. It was a "humongous compilation of activities." Pollution in that set-up came to mean outside contaminants, like trash and oil. With the SMART curriculum pollution meant an ecosystem out of balance.

Teacher 2: The first year students went to the river, they did tests for pH, macroinvertebrate Water Quality Index, and temperature, but they didn't know why they were doing these tests or what they meant. After SMART Science, they were much better prepared. They knew why they were doing the tests and could hypothesize about what might have caused possible pollution. These causes were not one-step (oil got in the water), but multiple step (algae grew too much due to fertilizer, this blocked out sunlight, plants died causing dissolved oxygen to decrease).

Teacher 3: The process of justifying choices that students had to make in SMART opened their eyes to what they were supposed to be looking for. If they went to the river without doing the SMART curriculum, they would take the critter sample and think everything was fine because there were critters in there. Students wouldn't know they needed to look for different types, so the sampling would just reinforce wrong ideas. Students would think pollution was just trash.

An interesting aspect of these comments, one that we have seen recur among students, teachers, and researchers, is that the teachers had been quite pleased with the river curriculum before they had completed the problem-to-project sequence. It was only after they had seen the big picture of what projects could become that they realized how much had been missing in their previous implementations of the river curriculum.

Contrasting Cases As Scaffolds

Another scaffold we have found useful comes in the form of contrasting cases. The use of contrasting cases is based on an experimental paradigm that derives from theories of perceptual learning (Bransford, Franks, Vye, & Sherwood, 1989; Garner, 1974; Gibson & Gibson, 1957). This paradigm is to ask people to analyze the differences between two or more examples. This helps them notice dimensions of information that they may otherwise miss if only considering a single example. For example, comparing two wines side by side can help one notice a distinctive flavor in one of the wines. In more conceptual domains, contrasting cases can also help students notice relevant features, and they can prepare the students for an explanation about why those features are significant (Schwartz & Bransford, in press).

In the context of the SMART River project described previously, we have provided students with catalogs of contrasting scientific instruments, some real and some bogus. Figure 3 provides a sample of entries from a catalog designed to help students learn about the role of macroinvertebrates in monitoring a river system. The students' task is to "order" the tool that will help them test for pollution. As they look through the catalog and begin to notice contrasts between the entries, they develop specific questions for which they need answers. For example, they want to know whether they should count the total number of macroinvertebrates or the number of kinds of invertebrates. The contrasting cases did not provide this knowledge. Instead, we used the catalogs to create an opportunity for self-assessment and to create a need to know. Students were quite interested to explore the textual resources we provided to help them make appropriate choices. Moreover, after students made their choices, feedback was made available via an interactive web site where students ordered their items and then got to try them out in a computer simulated river. The feedback they received by trying their catalog choices on the simulated river may also be thought of as providing a contrasting

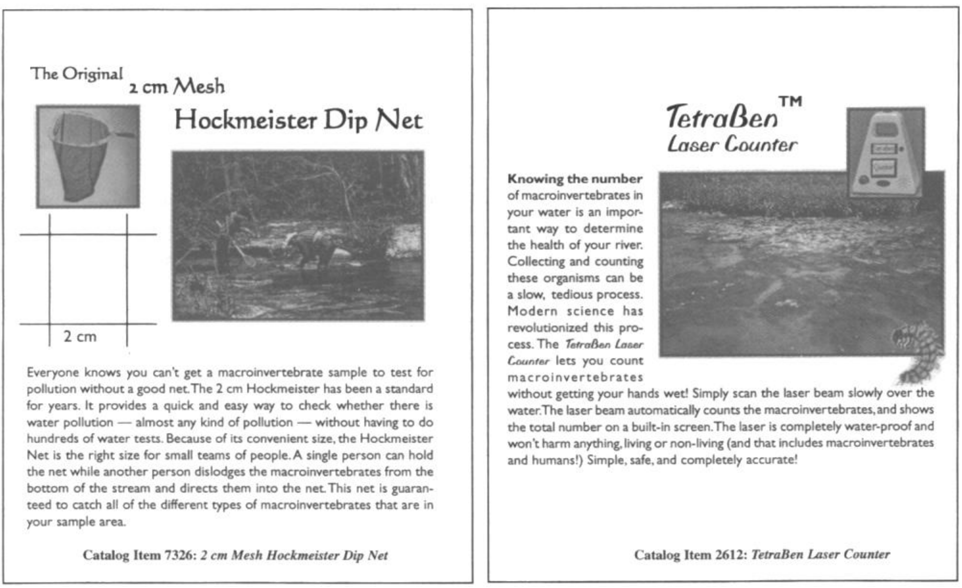

FIGURE 3 A sample of items from a catalog for ordering tools for testing macroinvertebrates in monitoring a river system.

case—a contrast between what the students expected to happen and what actually happened. This helped the students self-assess their knowledge and notice what things they still needed to learn.

Frequent Opportunities for Formative Self-Assessment and Revision

A third design principle for problem- and project-based instruction that we would like to highlight is the provision of frequent opportunities for formative assessment by both students and teachers. Most projects that we have observed in classrooms involve no explicit formative assessment. As a result, it is not clear to the teachers what is and what is not being learned, and it is not clear how to adapt their instruction accordingly. The few classrooms we have observed that do involve formative assessment have featured assessments by teachers but do not include systematic attempts to bring students in on the process. This seems like a missed opportunity for learning. An emphasis on self-assessment helps students develop the ability to monitor their own understanding and to find resources to deepen it when necessary (Brown, Bransford, Ferrara, & Campione, 1983; Stiggins, 1995). Learners get opportunities to test their mettle, to see how they are doing and to revise their learning processes as necessary. Without these assessment opportunities, the quality of learning can be disappointing—yet, this is not discovered until the end of the project when it is too late to change and revise the process.

Many of the scaffolds that have been discussed in the preceding section are, in part, designed to facilitate formative assessment. For example, allowing all students to begin with a common, complex problem such as *Jasper* or *Scientists in Action* provides a common ground for conversation that helps students communicate and, in the process, discover ideas and solution strategies that may need to be revised. Similarly, the use of contrasting cases helps students discover the importance of various issues (e.g., knowing the size of macroinvertebrates) despite being novices in the domain. Additional ways to support formative assessment have been explored in the SMART assessment project in which we created a classroom culture that supported frequent assessment and revision (Barron et al., 1995; CTGV, 1994). Revision was not seen as a chore but rather as a natural component of learning and growing. In this project, we have experimented with explicit cycles of assessment, feedback, and revision centered around student-generated products such as blueprints or business plans. In addition to changing the classroom culture, we support the assessment and revision process with content specific resources. These resources allow students to compare their solutions with solutions and explanations generated by others around the country who are working on similar problem- and project-based curricula. In these cases, the assessment is generated by both teacher and student, and it is followed by opportunities to revise the product that has been assessed. Later in this article, we discuss in detail the types of resources we have created that support these activities.

Social Organizations That Promote Participation and a Sense of Agency

A fourth characteristic of successful attempts to introduce problem- and project-based curricula involves the careful attention to the social organization of the classroom. Embedded within the three previous design principles are ways to support the student's movement from a passive receiver of already established knowledge to an active, reflective learner. This emphasis on developing a sense of agency as well as competence is being increasingly built into new learning environments (e.g., Brown & Campione, 1996; Collins, Hawkins, & Carver, 1991; Greeno, Collins, & Resnick, 1996; Scardamalia & Bereiter, 1991; Schwartz, in press). There are many ways to support active, reflective learning. Small group interactions, opportunities to contribute, peer review, and having access to data about how others have thought about the same problem are all methods discussed in this article that we have found powerful. For example, when students work collaboratively in groups, it is useful to establish norms of individual accountability (Johnson, Johnson, Holubec, & Roy, 1984; Slavin, 1983). One way to do this is to set up a requirement that each person in a group has to reach a threshold of achievement before the group can move on to collaborate on a more challenging project; for example, each individual must explain how pollution affects dissolved oxygen before the group can monitor the river. Under these conditions, the group ideally works together to help everyone succeed.

Beyond these organizations for learning, we have found that breaking down the isolation of the classroom can also be a powerful way to support learning through social mechanisms. We have experimented with this by designing performance opportunities in which students present their ideas to outside audiences. One reason why we have stressed outside audiences stems from an analysis of our own work environment and our observation that outside audiences (complete with deadlines) play extremely important roles in our work life (Barron et al., 1995). Connections with other communities are an important part of what makes our work meaningful, and they almost always offer new opportunities for learning. Not only do we learn from the varieties of feedback given from audiences with different concerns such as principals, parents, and fellow academics, but we also learn about more effective ways to communicate our ideas.

In the case of our middle-school learning environments, outside audiences also serve a quality control function. For example, in the case of projects that follow the completion of the *Jasper* adventure *The Big Splash,* students create a business plan and then prepare a presentation to convince others that it is feasible and that they deserve funding. These presentations are videotaped and evaluated by adult members of the learning community. These presentations, coupled with authentic outcomes and fairly explicit criteria for what counts as a good plan, can provide a strong incentive to prepare and revise. Additionally, they can help unite teachers and students because of their common outside challenge (e.g., see CTGV, 1997). Next, we share the details of how these ideas were implemented in a research project organized around blueprints and geometry.

INTEGRATING THE FOUR PRINCIPLES: SMART BLUEPRINT

In this section, we describe an instructional intervention, called SMART that integrated the four design principles, and we present some examples of student products. Afterwards, we formally document some of the benefits SMART had for the learning of fifth graders. The main components of the SMART instructional model are represented in Figure 4. We posted a similar but more child-friendly version of Figure 4 in the classrooms. We have found that the representation helped students and teachers continually reflect on the relation of their current work to the larger goals (or big picture) of their activity. It is hoped that it may also help the reader see the larger picture behind each of the instructional moves we describe next.

Learning-Appropriate Goals That Support Standards-Based Content

We designed SMART with learning-appropriate goals that were intended to foster learning activities and outcomes consistent with the ideals advocated by the NCTM (1989). These include opportunities to engage in sustained problem solving, planning, problem formulation, and the application of math concepts to real world contexts. *Blueprint for Success* (*Blueprint*), the *Jasper* adventure that anchors the problem-based learning in this implementation of SMART, offers students the opportunity to learn how basic principles of geometry relate to architecture and design. Students need to design blueprints for a playground that could actually be used by a builder, and they learn to use and justify aspects of a blueprint such as scale and multiple viewpoints. At the same time, they learn mathematical content such as the relation between perimeter and area as they try to optimize their use of materials. Constraints, such as the amount of fence available to enclose a playground lot, were included as part of the challenge to help focus the students' attention to the relevant concepts they needed to learn. The goal of the project-based component—designing a playhouse that would be built for a community center (if satisfactory)—also required the use of many geometric concepts. In addition to those found in *Blueprint*, it required that students be able to create consistent two- and three-dimensional representations

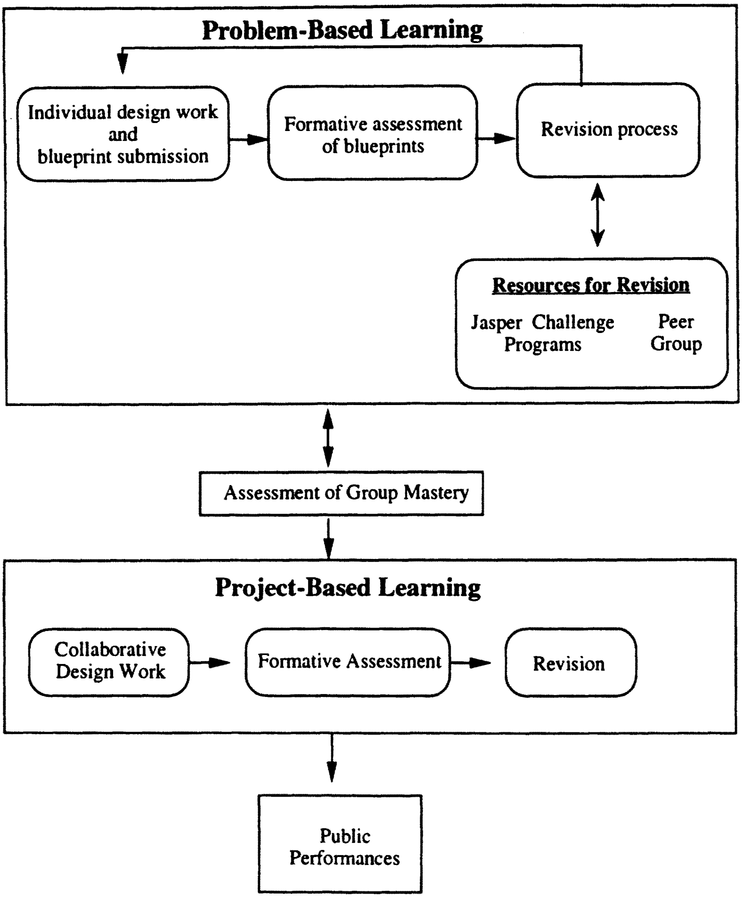

FIGURE 4 Problem-to-project-based model for SMART blueprint.

of their playhouse and explain the features of each. The design constraints that sustain learning-appropriate goals are described more fully in the following section.

Problem-Based Goals

The problem-based learning revolved around the video-based anchor *Blueprint*. In *Blueprint*, we meet two students, Christina and Markus, who visit an architect's office for career day. The story begins with a dramatic scene in which a friend is playing in the street and is hit by a car. Although the accident did not result in serious injury, the incident prompts a local developer to donate land. The developer comes to the architect's office while Christina and Markus are visiting. Christina and Markus suggest that a playground be built on the donated property to provide a fun spot for children to play. The developer agrees with this idea and invites the children to design the equipment and park layout and to complete the needed blueprints. The story ends with a summary of the materials that have been donated by the local businesses and a challenge to children in the classroom to develop the plan. Specifically the challenge is to:

- Create a design or model of the playground for the builders.
- Provide a site plan of the lot, the playground, and each piece of equipment.
- Provide a front and side view of the equipment with relevant angles, lengths, and depths.

At the end of the story, students find out that community organizations and businesses have agreed to donate building supplies. Specifically, they are told that a fencing company has donated 280 ft of fence, that another company has donated 32 ft^3 of sand as well as sliding boards for a slide, and that a construction company is donating all the wood and fine gravel to cover the lot. The students are asked to specify how much wood, gravel, and sliding board they will need. In addition, students are given a list of safety requirements that specify appropriate ranges of angles, depth of gravel needed, and distances required between pieces of equipment. These materials and safety requirements then become constraints for students to attend to as they complete their designs.

Project-Based Goals

From the outset of the problem-based work, children are aware that their work on *Blueprint* is preparing them to design a playhouse for young children that may actually be built and donated to community centers in local neighborhoods. The students in our classes know the project-based component of the instruction by the name *The Big Challenge,* and there is considerable excitement generated by the idea that their design might actually end up being used by young children. Students also know that for their design to have a chance of being built they must make an accurate blueprint and scale model. Students were given the following design constraints for the playhouse:

- Children who are 4- and 5-years of age will play in it.
- Only two sheets of wood, each 4 ft by 8 ft can be used to build the playhouse. The walls, roof, and trim must all come from this wood. Your design should use as much of the two sheets of wood as possible.
- The playhouse must have three walls and a flat roof.
- The floorspace that the playhouse covers must be between 10 and 20 ft^2.

- Any openings for doors and windows must be safe. They must be larger than 7 in. or smaller than 4 in. to prevent children from putting their heads into an opening and getting stuck. There should not by any V-shaped openings.

Finally, they are told that they will explain the blueprints and scale models they create on videotape so that they can be evaluated for accuracy and consistency with problem constraints. The evaluators in this case are not their teachers but an outside audience known as "*Jasper* Central." This structure frees the teacher to join with the students and serve in the role of coach. The final presentation is an important aspect of the projects. They provide students with an opportunity to reflect on issues such as what it means to explain one's thinking and how to convince someone of the accuracy of a plan as well as issues such as what makes a presentation engaging. The guidelines for the presentation were as follows:

- Every member of your group must speak during the presentation;
- The presentation should be 5 to 10 min long; and,
- Convince *Jasper* Central of the following:

  1. The design uses as much of the available wood as possible but no more than the available wood.
  2. The playhouse is safe for 4- and 5-year old children.
  3. The playhouse is fun to play in. Use your imagination and be creative.

Scaffolds and Social Organizations That Support Teacher and Student Learning

In our preceding description of the learning-appropriate goals, we indicated a problem- to project-based sequence. As described earlier, the use of a problem-based experience prior to a project-based experience serves as a form of scaffolding. In this section, we describe several additional ways that we supported student and teacher learning in the problem and project phases of SMART. Rather than organizing these points according to the relevant design principles, we have grouped them according to how they appeared to the students and teachers. So, for example, a series of video programs that supplement *Blueprint*, called the *Jasper Challenge* programs, include just-in-time instruction as well as contrasting cases of student presentations that stimulate classroom conversation about social norms of acceptable understanding.

Just-In-Time Scaffolds for Blueprint

Without scaffolds, the fifth-grade students with whom we work would have considerable difficulty solving *Blueprint*. The students typically enter the problem with little experience using concepts such as scale and area, and sometimes they have trouble with basic measurement. One way to approach this situation would be to teach students the relevant concepts first. We have found, however, that students find it much more interesting to learn about these concepts in the context of their own design work when they have developed a need to know. Several different types of scaffolds accompany *Blueprint* to support this just-in-time learning. These are described next.

Embedded teaching. The embedded teaching scenes in *Blueprint* present ideas for how to do something without actually providing answers to the challenges (Zech et al., in press). In one scene, for example, an architect points to a drawing of a swingset design that shows a front, top, and side view. However, there are no dimensions provided on the drawing. Consequently, students can return to this embedded teaching scene to get an idea of these different views, but they cannot simply copy answers to the challenge they face. Another embedded teaching scene shows the use of graph paper and a protractor to determine the length of the legs needed to make a ladder of a certain height. None of the particulars from this example are used in the solution to *Blueprint*, but the general idea of using graph paper is a very important scaffold that students and teachers use.

The Jasper Challenge programs. Other types of scaffolds occur outside the video adventure itself in the form of teaching tools. These can be shown on a just-in-time basis by teachers. They take the form of the *Jasper Challenge* programs. The ones we will discuss were designed specifically for *Blueprint.* The *Jasper Challenge* programs contain four segments that differ in their emphasis, although they share the purpose of supporting formative assessment, reflection, and contact with a larger community. The four segments are called *Smart Lab, Toolbox, Kids-on-Line,* and *The Challenge.* There are three programs (four segments each) that support *Blueprint.* The content of each program is coupled with a specific aspect of the design task. For example, teachers usually help students to organize their problem solving by asking them to begin with the task of designing the swingset and slide. The first *Jasper Challenge* program focuses on this task, and students use the program after they have finished an initial set of blueprints and obtained some feedback on them. Table 1 summarizes the content of each segment of the three programs. As this table reveals, the content not only covers specific design tasks but also covers discussions of mathematical concepts including scale, area, volume, perspective drawing, and angles. The purpose and format of each segment is described next.

Smart Lab creates a virtual community for students. It is designed (a) to stimulate students to reflect on their own thinking relative to a larger student community and (b) to engender discussion about criteria for judging the adequacy of various solutions. The host of *Smart Lab* summarizes data that have been generated by students in a number of classrooms. For example, in *Blueprint* there is a specific amount of fencing available to enclose the playground. Figure 5 shows a visual from one portion of a *Smart Lab* that presents the four most common designs among 100 students who had been working on this problem. The dimensions are not all ideal or even feasible; one is too large for the amount of available space, another is too narrow to fit the playground equipment, and so forth. The teachers have found that these contrasting designs effectively anchor a discussion of the importance of considering shape and size when designing the site plan.

The *Toolbox* segment introduces visual representations that can be used as tools for problem solving. One segment, for example, introduces the idea of a graph paper ruler that can help determine the length of diagonal lines drawn on graph paper (see Figure 6). Students use this tool to help them establish the length of the legs in their own swingset designs. *Toolbox* makes extensive use of dynamic visual representations to explicate the concepts. For example, an extremely helpful visualization is one that helps students see what it is like to "fly" above a swingset or slide so that they can see what these look like from a top view (i.e., they have no apparent angles). In addition to helping students construct mental models, these dynamic visualizations encourage discussions about concepts rather than procedures for computing answers.

Whereas *Smart Lab* offers frequent (and sometimes conflicting) problem solutions, *Kids-on-Line*, the third program segment, offers student presentations made by child actors. By scripting presentations for the actors, we were able to seed the presentations with typical errors without embarrassing students. This design feature allows the classroom students to engage in critical analyses of the arguments that are presented by the actors. At the same time, the actors provide students with a chance to pattern themselves on same-age peers explaining their work in sophisticated ways.

The fourth and final segment is called *The Challenge. The Challenge* serves three main functions. First, it supports the notion that work is a process and can be improved through revision. Second, it alerts students to the next phase of the problem that they will be tackling. Third, it enhances the sense that the students are a part of a larger problem solving community working on this challenge. *The Challenge* typically asked students to revise their work based on what they learned in the *Jasper Challenge* program, and it asked students to begin work on a new part of the problem. For example, one *Challenge* suggests that students should revise their top view of the slide and swingset if they needed to and that they should begin working on their site plan.

Cycles of Assessment and Revision

Students' understanding of geometric concepts is deepened through feedback about the blueprints they create, followed by revision of their designs. Students improve

TABLE 1

Contents of the *Jasper Challenge* Programs Designed for *Blueprint for Success*

Show	*Smart Lab*	*Kids-On-Line*	*Toolbox*	*Challenge*
Form and content of segments	Representation of student-generated answers to questions about central concepts and student design work	Presentations by child actors of design work that include common errors as well as examples of sophisticated reasoning	Discussion of mathematical concepts by two characters, Dave and Steve, and useful representations for problem solving	Wrap up of show by the host that includes directions to revise and to start on the next part of the design work
1	(a) What is a scale drawing? Four most common answers represented in a bar graph.	(a) Presenter 1 shows blueprints in which all measurements correspond the actual length of dimension on drawing. All are in inches.	(a) Discussion of the concept of scale takes place between Steve and Dave, the *Toolbox Wizard*. Scale is explained by showing full scale, half scale, and 1/8th scale representations of Steve. The issue of how representations that are different sizes could all represent the actual size of the same real world object.	(a) Steve directs students to rethink the measurements of their swingset and slide.
	(b) What is the height of your swingset and what is the length of the legs? Data represented in a scatterplot. (c) What is the angle of your slide?	(b) Presenter 2 shows the front view of a swingset design: Typical error of leg length equivalent to set height is made on presented blueprint.	(b) Steve expresses confusion to Dave about how one measures diagonal lengths on graph paper. Use of graph paper ruler to measure legs of swingset is introduced and demonstrated.	(b) Steve tells them to draw their site plan and to include top view drawings of swingset and slide in this representation.
2	(a) Now that you have revised your swingset design, what is the height of your swingset and the length of the legs?	(a) Presenter 1 designs a playground that is 20 ft by 120 ft. His rational the shape is good for playing ball. He neglects to realize that a 20-ft width would create a narrow space. He also shows his revised swingset design.	(a) Steve expresses confusion about how to imagine what a top view of a piece of equipment might look like. An animation is used to view pieces of equipment from the top, side, and front views.	(a) Steve directs students to revise their top view drawings, to revise their playground dimensions.

	(b) What are the dimensions of your playground? Four site plans are presented with different dimensions.	(b) Presenter 2 designs a lot that is 70 ft by 70 ft and explains her rational for the importance of maximizing area. She also shows her placement of equipment on the lot. She has erroneously drawn front and side views, not top views.	(b) Steve and Dave discuss different ways of using the given 280 ft of fence. The relation between the shape of the playground to area is explored.	(b) Steve directs students to begin working on their sandbox designs and asks them to create drawings that include the dimensions of sandbox.
	(c) What does the top view drawing of your swingset look like? Three top view drawings of swingsets are shown; two are incorrect.		(c) Dave shows Steve how to use string and graph paper to experiment with different shapes of site plans. He introduced how a table is a useful tool to record and keep track of the relation between different dimensions and area.	(c) Steve directs students to design a fourth piece of equipment.
3	(a) What are the dimensions of your sandbox? Three common designs for sandboxes presented. (b) What kind of playground equipment did you choose to design for the fourth piece of equipment? (c) How much gravel do you need to cover the playground so that you meet the safety requirements?	(a) Presenter 1 explains her design for a sandbox, depth not included in her blueprint. She explains how she used cardboard and real sand (measured in a three-dimensional cube created to scale) to confirm that her design would indeed hold 32 ft^3 of sand.	(a) Dave and Steve discuss the concept of volume. Dave uses 1 in. cubes used to represent a cubic foot of sand. Together they examine several ways to create a sandbox that hold 32 ft^3 of sand.	(a) Steve directs students to begin work on the *Big Challenge* of designing playhouses.

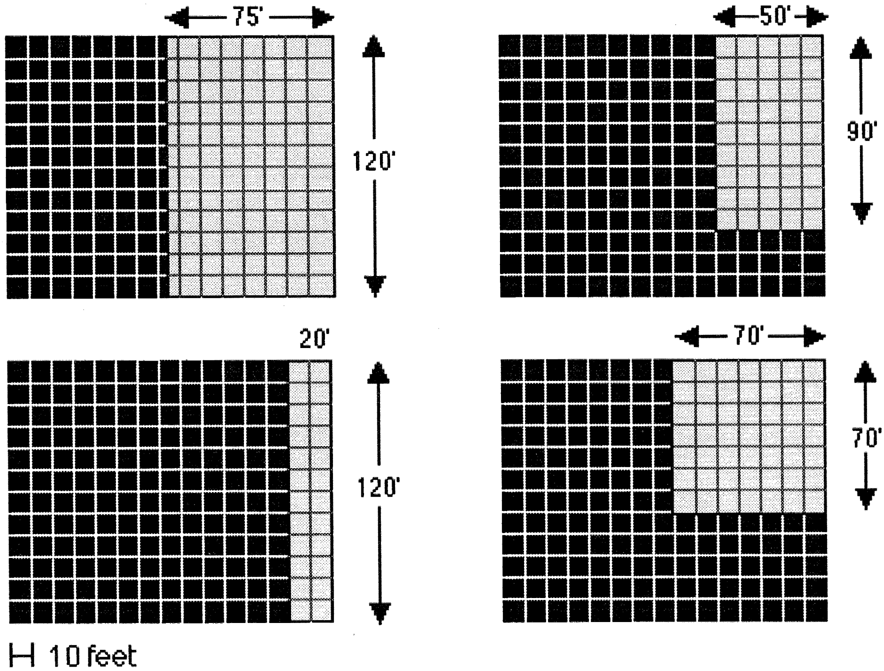

FIGURE 5 A scene from *Smart Lab* comparing the four most common playground site plans.

their own blueprints with the help of multiple resources including their peers and feedback from the teacher. Three cycles of design, feedback, and revision occur as students develop different aspects of their blueprint.

To help students in the revision process, teachers are encouraged to comment on the use of scale, consistency of scale and measurements, perspective, and the reasonableness of dimensions. Our instructional goal, however, is not limited to helping students learn the key concepts; we also want to help the students become lifelong learners. Therefore, teachers do not specify exactly what needs to be changed; their feedback is relatively general and alerts students to key concepts that they need to rethink and learn about. To help the students take charge of their learning, the feedback suggests resources that students can consult to help with the concepts. The feedback, for example, may include laser disk numbers corresponding to relevant sections of each show. This makes it so that students can return to particular portions independently. When solving *Blueprint,* students might receive the following feedback about their use of scale: "Recheck your blueprints. I used your scale and came up with different measurements than you did for some parts of your drawings. You might watch *Smart Lab* to help you." By providing this type of feedback rather than feedback that is more directive or summative, we and the teachers are attempting to empower students with intellectual responsibility. To help teachers with the task of providing feedback, we made a simple Hypercard program that allowed teachers to evaluate the relevant dimensions for a particular task and then to print feedback for students (see Figure 7).

To develop a more concrete understanding of the assessment-revision cycle, one may examine Figures 8, 9, and 10. Respectively, they show an example of one student's original blueprint of a swingset, the feedback provided by the teacher, and the revised blueprint following peer and resource consultation. As may be seen, the first drawing has no measurements or indication of scale, and the front view of the swingset shows slanted legs as would be seen from a sideview. These are very typical errors. The feedback from the teacher includes relevant comments and refers the students to additional resources including the *Jasper Challenge* programs, peers, and other resources included on the videodisk. The posttest drawing is much improved, although not completely without error. These types of changes were common across our classes. However, this example is for illustrative purposes only. Next, we report some of the data we have been gathering.

GENERAL ASSESSMENT OF THE SMART MODEL

Our research on this model is ongoing. Consistent with the goals of a genre of research that has been called the "design experiment" (Brown, 1992), it has been

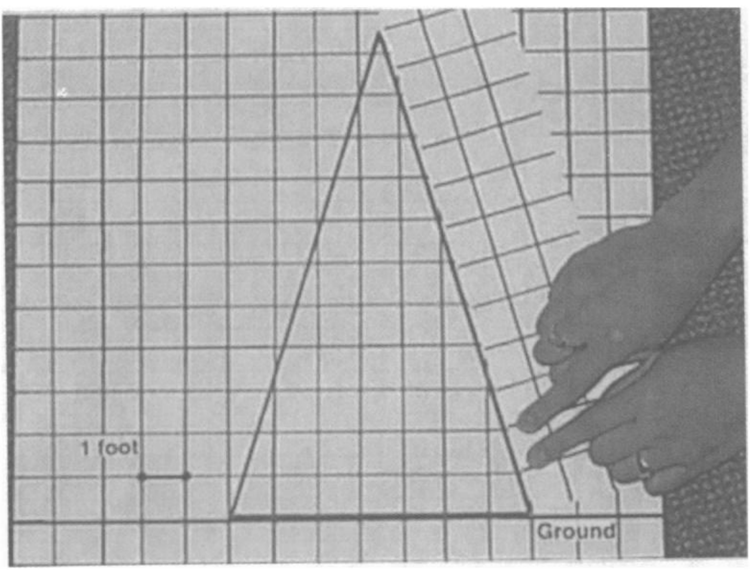

FIGURE 6 Visual tool to help students make a graph paper to measure lengths in scale drawings.

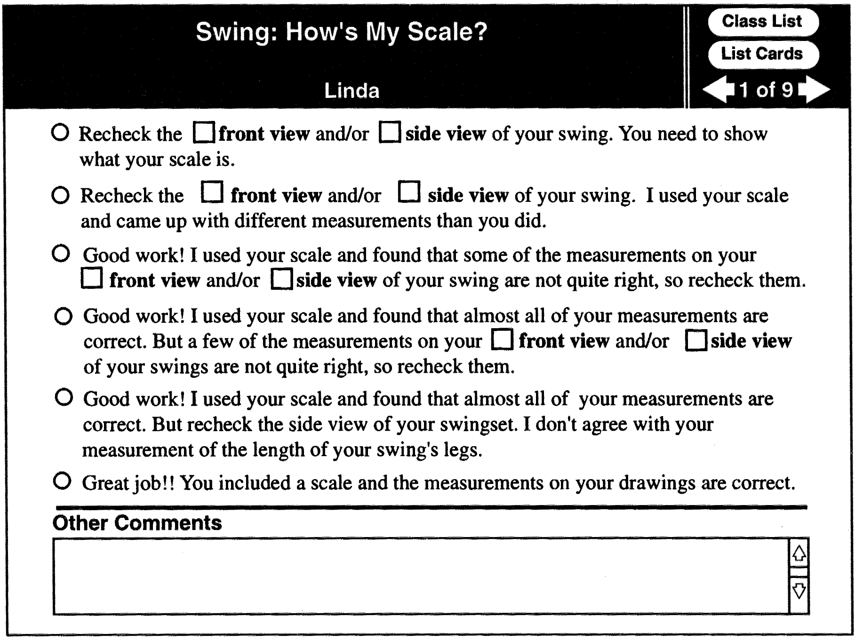

FIGURE 7 Interface of Hypercard program for helping teachers give feedback about blueprints.

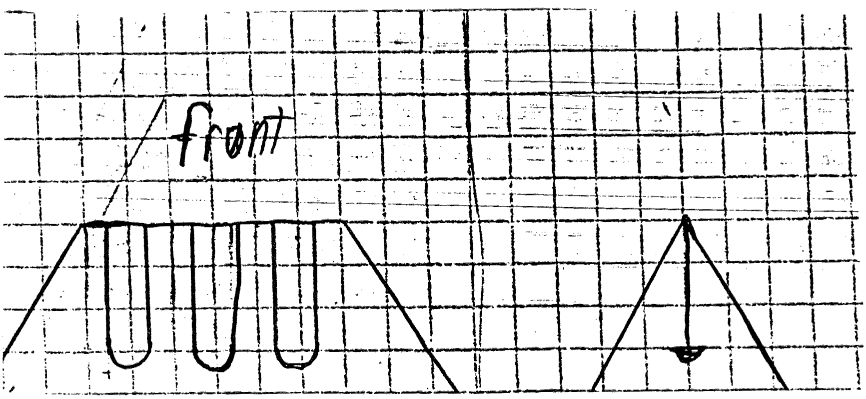

FIGURE 8 Example of a student's first attempt at a swingset design.

Slide: How's My Scale?

→Recheck the front view and side view of your slide. I used your scale and came up with different measurements than you did. Again, here were no measurements, so I used the scale to figure out the size.

If you need help on scale: Watch Toolbox in Show 1 OR Watch Blueprint for Success (Frame #9409 – 13154) OR Ask someone in your group for help.

Slide: Did I Label the Important Measurements?

→Recheck the front view and side view of your slide. Most or all of the important measurements are not labeled. Don't forget the angle of the slide.

If you need help: Ask someone in your group for help

What about the Size of My Slide?

→Recheck the size of your equipment. The side view of your slide is too small. Some sizes are realistic, and others are too small.

If you need help on scale: Ask someone in your group for help OR Measure the slide in your school's playground.

Slide: Did I Draw My Front and Side Views Like an Architect Would?

→Recheck the front view and side view of your slide. Some parts do not look exactly like what an architect would draw.

If you need help: Watch "Drawing Like an Architect: (Frame #49397 – 52171) OR Watch first half of

FIGURE 9 Feedback given on a first attempt at a swingset design.

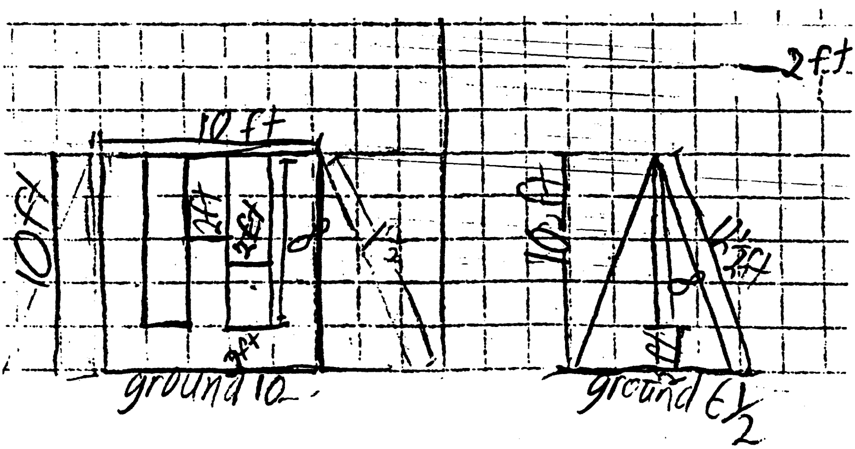

FIGURE 10 Revised swingset following feedback and use of program and peer resources for revision.

our intent to gather information from both students and teachers that will help improve the learning environment as well as inform theory. In some of our studies, we have used comparison groups to assess the value added by *Jasper Challenge* programs versus *Jasper* alone (e.g., Barron et al, 1995; CTGV, in press). In this study, we did not include a comparison group because all teachers wanted to be in the experimental group, and we agreed that they should be. Nevertheless, we were able to gather measures of learning that are specific to the nature of our intervention. Although this research encompasses issues of teacher learning and motivation, we focus on student learning here. Specifically, we present evidence that students learned standards-based geometric concepts, that they learned how to communicate their ideas, that they benefitted from the process of revision, and that their work on these problems and projects was memorable.

Our collaborators in this research were 5 fifth-grade classes that included 111 students and 5 teachers. The classes all came from the same middle school located in a metropolitan area of Nashville, Tennessee and were eligible for Title 1 assistance. Students worked for approximately 5 weeks on the problem and project components of the lessons. Instruction occurred 4 days per week in 45 min periods.

Student Learning

We report three measures of student learning. First, the design-a-chair task, is a performance assessment that evaluates how well children tackle a new design problem. The second measure captures the broad range of standards-based geometry concepts that were relevant to *Blueprint* and the project. The third measure reflects the success with which students collaboratively designed their playhouse projects. Each measure provides a different perspective on the benefits of these problem- and project-based learning experiences.

Design-A-Chair Task

In this task, students received a written scenario in which they were told that they had been given the job of designing a chair for young children. They completed this task in pretest and posttest fashion. Their job was to draw blueprints for carpenters who live far away and with whom they would not be able to communicate. The intent of our instruction was to encourage students to specify all the design information that a builder would need. The specific instructions included the following:

- Your task is to make a blueprint for a chair designed for a 3 year old.
- Use the graph paper on the back of this page to make your blueprint.
- Be sure to include all the information the carpenters will need to make the chair just the way you want.

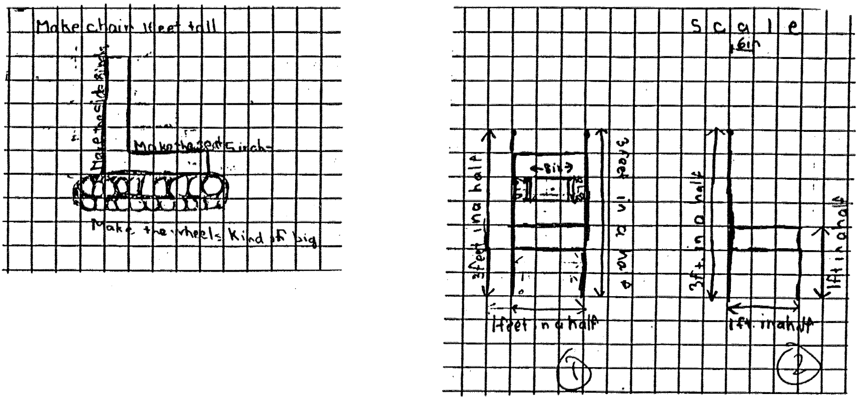

FIGURE 11 Pretest and posttest blueprints on the design-a-chair task.

- The carpenters will not start building unless they have a clear and precise blueprint to work from.

We chose this task because we thought it would illuminate aspects of understanding that should have been improved through the problem- and project-based work. In particular, we hoped that students would come to understand that design work should meet the real-world constraints set out by the design task. These included the need to think about the user (the chair should be of an appropriate size for a small child) and the needs of the builder (measurements of each piece of the chair should be provided including height and width of various pieces such as legs, seat, arms, and back). Given that students had designed playgrounds and playhouses with these types of considerations in mind, they should be able to transfer them to the new design task.

Figure 11 provides a prototypical example of one student's blueprint before and after the intervention. To document the generality of these types of changes, the pretest and posttest drawings for each student were shown to a reviewer. The reviewer's task was to classify drawings according to whether they were from the pretest or posttest. Based on this analysis, the reviewer was able to correctly classify each student's pretest versus posttest drawings in 97% of the instances. In short, almost everyone improved.

Two reviewers jointly evaluated the chair blueprints on the dimensions of scale and measurement. The students received one point for each of the following with a maximum of 5 points:

- Draws a picture;
- Shows a scale;
- Shows measurements;

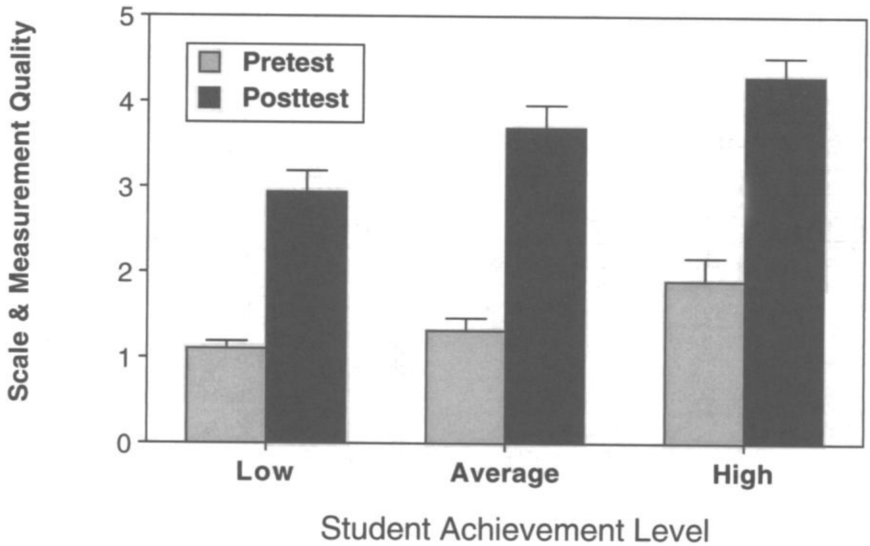

FIGURE 12 Quality of scale and measurement in students' chair blueprints.

- Implicit consistency: Scale can be inferred from measurements;
- Explicit consistency: Measurement labels are consistent with indicated scale.

To see if the effects of the problem- and project-based instruction were general to all the students, not just to the high achievers, the data were partitioned as a function of prior mathematics achievement (as measured by the Tennessee Comprehensive Assessment Program). Students in the low-achievement group had scores ranging from the 1st to the 33rd percentile (n = 42, X = 19.5, SD = 7.9), students in the average-achievement group had scores ranging from 34th to 66th percentile (n = 38, X = 49.1, SD = 9.7), and students in the high-achievement group had scores that ranged from 67th to 99th percentile (n = 28, X = 81.3, SD = 8.6). As Figure 12 indicates, all three achievement groups improved. To test the statistical significance of these gains, a mixed model analysis of variance (ANOVA) used time of test as a within-subject factor and achievement level as between-subjects factor. The results indicated a main effect of time, $F(2, 105) = 133.21$, $MSE = 1.9$, $p < .01$; and a main effect of achievement level; $F(2, 105) = 12.73$, $MSE = 1.5$, $p < .01$, with no interaction between the two.

Figure 13 shows the percentages of students who designed a chair that was an appropriate size for a young child. Again, there was substantial improvement with 71% of the students moving from either no measurements or unrealistic measurements to the use of realistic measurements. These gains were consistent across the achievement levels. A loglinear analysis compared the percentage of students who showed gains in the use of realistic measurements from pretest to posttest across the three achievement levels. There was a significantly larger number of gainers than nongainers, $Z = 3.7$, $SE = .11$, $p < .01$, and there was no effect of achievement level, for all contrasts, $Z < .5$, $SE = .16$, $p > .3$. These gains in the use of realistic measurements suggest that students became more attentive to real-world constraints as a consequence of the instructional sequence.

Geometry Test

The design-a-chair task investigated how well students understood issues relevant to communicating their ideas in the context of a blueprint. In addition to those gains, we expected that the students would gain on the standards-based geometry concepts that were targeted by the learning-appropriate goals (see previous section). To determine if this was true, students completed a "traditional" test that covered scale, volume, perimeter, area, units of measurement, and perspective drawing. Nineteen multiple-choice items (available from the authors) asked students to determine the relevant quantities from figures and to identify correct strategies for determining these quantities.

The percentage correct was analyzed as a function of prior mathematics achievement and time of test (preinstruction or postinstruction). As the data in Figure 14 indicate, students in all achievement groups made significant gains in their ability to answer questions related to the geometry concepts that were embedded in the context of *Blueprint* and the playhouse design task. The percentage increase was

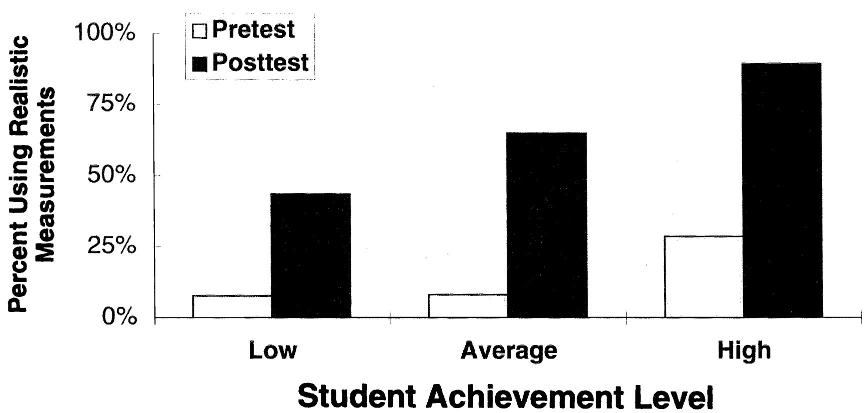

FIGURE 13 Use of realistic measurements in students' chair blueprints.

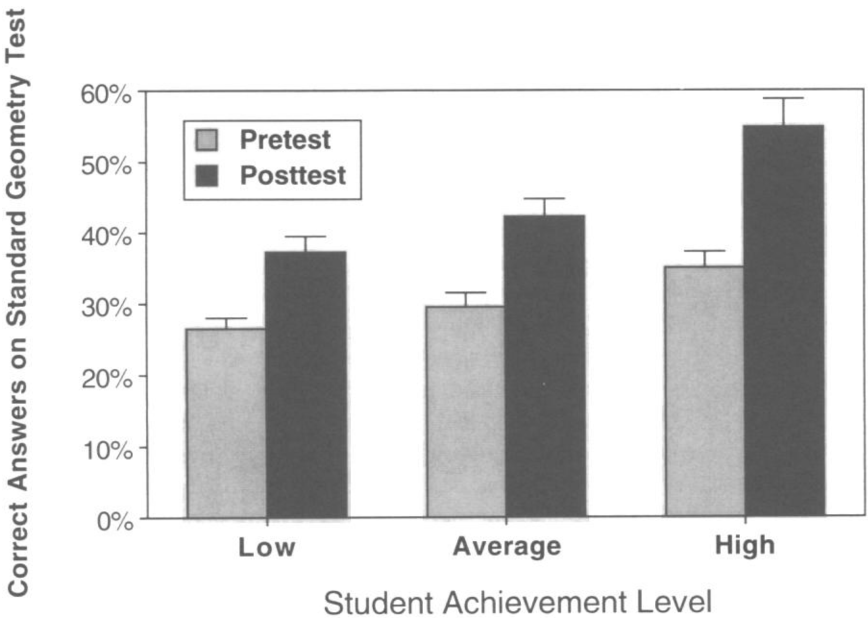

FIGURE 14 Scores on standards-based geometry test.

similar in each achievement group, suggesting that all students were able to benefit from their problem- and project-based work. To test the statistical significance of these gains, a mixed model ANOVA was carried out, with time of test as the within-subjects factor and achievement test level as the between-subjects factor. Only 64 students completed both pretest and posttest (21 low, 21 average, 22 high ability) and can be included in the analyses. The results indicate a main effect of time, $F(1, 61) = 77.14$, $MSE = 87.39$, $p < .01$, and a main effect of achievement level, $F(2, 61) = 8.97$, $MSE = 205.9$, $p < .01$, with no interaction between the two.

The Project's Playhouse Designs

Students worked in 1 of 37 small groups for approximately 1 week as they designed their playhouses, prepared their blueprints and scale models, and developed their presentations. Students were aware that each group's work would be evaluated by *Jasper* Central for accuracy, safety, and consistency. The presentations were additionally evaluated on how well they communicated important design features. All the designs that met the criteria were entered into a random drawing to see which ones would actually be built. Of the 37 designs submitted, 84% were judged to be accurate enough to be built. This is a high rate of achievement. (Those that were not deemed accurate generally suffered from inconsistencies between the scale model and the blueprint or did not meet the safety constraints.) The success rate indicates that students were generally able to organize themselves as small groups and complete the work of drawing blueprints, building three-dimensional scale models that were consistent with the blueprints, and preparing formal presentations for filming. This was especially impressive given that they only had about 1 week to complete their work.

One of the nice aspects of well-designed projects is that the students often have room to express their creativity in a way that complements their understanding rather than detracting from it. Playhouse themes ranged from a "surfer shack" to "the playhouse of the world", the latter adorned by a colorful image of the earth. Some of the presentations included songs, costumes, characters, and soapbox speeches. The Appendix includes the full text from one of the presentations. Three class members worked on this design and presented it. The playhouse they created took the form of a schoolhouse. In keeping with the school theme, the presenters took on personas of teachers, dressing and speaking the part and letting the audience (their classmates in real time and *Jasper* Central as the film-watching audience) have the role of students. Figure 15 shows the presenters in action. Although their design and presentation had flair, the students were also very attentive to the design constraints and communicative demands of the task. They took seriously the need to convince *Jasper* Central (the outside audience) of the accuracy of their work. They included information about safety requirements and their use of extra wood for trim, and they put forth effort to convince their audience that it would be fun for 4- and 5-year olds to play in.

In summary, across the three measures of learning, students showed substantial gains in their abilities to understand, use, and present geometric concepts. We are particularly encouraged by these results because students at all levels of mathematics achievement levels made significant strides on all measures.

FIGURE 15 Students making videotaped presentation of blueprint and scale model of their playhouse design to *Jasper* Central (the outside audience).

Students' Adoption of Revision

As a consequence of the SMART emphasis on formative assessment and revision, we thought it was important to determine whether students understood and capitalized on their feedback and opportunities for revision. Students in traditional classrooms do not normally revise. For example, when we asked a subset of the students (see the following) if they had ever done any revision before, 24% reported that they had not. When students did describe a revision experience, 63% of the time the revision involved a low-level cognitive task like checking spelling or making something neater. Thus, it was not obvious that students would understand or accept the revision process.

The teachers reported that they were extremely surprised at how readily students revised their blueprints; they had expected the students to complain about having to redo their work. One possible explanation for the lack of complaint is that the students understood that revision was going to be the norm in SMART. Another possible explanation is that the students appreciated the chance to revise and get things right. To explore these possibilities, we investigated student understanding of the revision process by conducting a series of structured interviews with 10 students from each of 3 classes. We interviewed the students after two of the three cycles of problem solving and revision. We first asked students "Did you revise your blueprints?" If the student answered "Yes" we followed by asking "What did you change?" and "How did you know that you needed to change that?"

The interviews indicated that students did take advantage of the opportunity to revise and that they used the wide variety of resources to help. These resources included the feedback sheets from teachers, comments from others in their groups, and the *Jasper Challenge* programs. At face value, the interviews revealed that students took advantage of the information-rich classroom that had been established. The teachers, however, had reservations about the extent to which students had used the feedback. They wondered about the accuracy of the students' reports. Although teachers reported that the assessment opportunities were useful to them, they were uncertain about its value for students. For example, they were concerned that the feedback was not specific enough for the students to use productively. As mentioned previously, we deliberately designed the feedback to be nondirective; we wanted to place some of the assessment responsibility in student hands. However, it was possible that we had not provided sufficient scaffolds for this to happen.

The original interviews did not let us know whether the students' reports were accurate. Given the concern of the teachers, we conducted another set of structured interviews that focussed on the feedback sheets. Because we had copies of the feedback sheets and the revised products, we could determine the correspondence between the student reports and the "facts." For this second set of interviews, we randomly selected a new group of students. We asked the students, 2 to 4 days after last seeing their feedback sheet, "What did your feedback sheet say?" All students offered one or more things that their sheets said needed revision. Of all the feedback items the students reported, they were accurate 77% of the time. In sum, the students did not necessarily report everything from their feedback sheets, but their reports were quite accurate. The interviewers also asked students to indicate what changes they had made in response to their feedback. Every student made at least one revision suggested by the feedback, and 49% of the total suggestions were followed. In those cases in which students did not follow the feedback directly (e.g., measuring or adding labels), they tended to redraw the design and change the dimensions. This suggests that even though students may not have always known specifically how to revise, they at least understood what to revise. Evidently, the students did read and think about the feedback they received.

Students' Reflections on the Importance of Their Experiences

Although students had to revise, and although the SMART intervention lasted over a month and the students had to learn complex content, they worked with enthusiasm. Working toward doing with understanding does not need to reduce student motivation. For example, the students completed a second round of SMART in the spring in which they solved *The Big Splash* and created a business plan for a school fun fair. Their interest and energy continued unabated. Based on the evident classroom enthusiasm, we became curious about whether these experiences made a lasting impression on students. To investigate this issue, we interviewed a group of the students the following fall. The interviews were conducted by people whom the students would not associate with Vanderbilt University or their fifth-grade *Jasper* projects. The interviewers asked the students to think about last year when they were fifth graders and to describe things that made them feel (a) proud and (b) creative. Interviewers also asked students to name things that they would like to do again. Across the three questions, more than 50% of the students spontaneously mentioned "Jasper" (which in their minds included the projects that followed *Jasper*) as something that was very special to them in fifth grade. When students were explicitly asked about *Jasper* later in the interview, nearly all said that it was a very important experience for them.

CONCLUSIONS

In closing, we provided examples of how the process of reflecting on one's own learning and improvement can be facilitated by the provision of resources and the encouragement to take responsibility for one's learning. We described how this process is an especially important potential of project-based learning because they can provide room for student agency. Not only do we want students to "do with understanding," but we also want them to "learn with understanding." We want them to understand why they are learning. Given the students' evaluations of importance, perhaps our SMART model, in which we integrated the four design principles, helped students develop a "wholeheartedness of purpose" (Kilpatrick, 1918) dedicated toward learning how to do with understanding.

It seems clear that the opportunity to complete something tangible, like a project to build playhouses for other children, has been a significant factor in the sense of pride and accomplishment expressed by students. Projects help realize Dewey's (1897/1974) vision of education as a "process of living and not a preparation for future living" (p. 430). Nevertheless, our work in classrooms convinces us that students' abilities to accomplish projects with understanding can be greatly enhanced. Our goal in this article was to share some ways that we have found to support doing with understanding. We believe this is an important goal because projects offer many attractive promises, but they are often difficult to implement. A major hurdle in implementing project-based curricula is that they require simultaneous changes in curriculum, instruction, and assessment practices—changes that are often foreign to the students as well as the teachers.

To frame these challenges, one may view the attempt to implement project- and problem-based learning in classrooms as project-based learning itself. It is a project for the teachers who try to make something happen in their classrooms. In addition, it is a project for the researchers who try to help teachers achieve their goals. As a result, it can take a long time for new innovations to begin to run smoothly in the classroom (Blumenfeld, Krajcik, Marx, & Soloway, 1994). Our approach to designing, implementing and evaluating problem- and project-based curricula has emerged from a long-term collaboration with teachers during which we have frequently revised our ideas. Thus far, we have collectively identified four design principles that appear to be especially important: (a) defining learning-appropriate goals that lead to deep understanding; (b) providing scaffolds such as beginning with problem-based learning activities before completing projects; using embedded teaching, teaching tools, and sets of contrasting cases; (c) including multiple opportunities for formative self-assessment; and (d) developing social structures that promote participation and a sense of agency.

These principles and the material supports we described are an important step forward. Nevertheless, our experiences suggest the need for new models of professional development that can provide inservice and preservice teachers with the opportunity to engage in the type of learning that we are recommending for students. One way to support teachers is to help them create clear models of possible student learning trajectories in the context of problem- and project-based learning before they enter the classroom. For example, it is possible to create learning environments for teachers that will help provide them with the big picture of what it means to enact problem- and project-based instruction and alert them to potential challenges that may arise. Designs for such supports are currently underway (Blumenfeld et al., 1991). It is also possible to help teachers be more aware of the variety of ways that students may understand, or fail to understand, the particular concepts that are embodied in the projects they wish to carry out. Organizing previously collected student products, such as the various artifacts described in this article, might be a powerful way to build up teachers pedagogical content knowledge (Shulman, 1990) and to ease the transition to problem- and project-based approaches. Although tools to help teachers prepare for problem- and project-based learning are important, support is also needed as teachers carry out problem- and project-based work. Teacher learning communities in the form of video clubs (Frederiksen, Sipusic, Gamoran, & Wolfe, 1997), face-to-face and online discussion groups (Schlager & Schank, 1997; Wineburg & Grossman, 1998), and collaborative teaching represent recent approaches that are proving to be successful alternatives to the traditional short-term, one shot models that have been prevalent and frequently less than successful. The research reported in this article leads us to be optimistic about the potential of problem- and project-based approaches to enrich learning. The ongoing challenge is to create supportive environments for the teachers who will realize this potential.

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APPENDIX
Children Presenting Blueprint for Playhouse

All presenters: [in unison] Good morning students.

Presenter 3: Hi, my name is Ms. Duncan.

Presenter 2: Hi, I'm Mr. Sircar.

Presenter 1: Hello, I'm Mr. Robert. I'm going to talk about the blueprint today. First I'd like to say, we started out with 4 by 8 pieces of plywood so each wall should be 4 by 4, 4 feet across and 4 feet up. Our scale is 6 in. for one block (points to scale on blueprint). Now I'll talk about the front. The window is 9 in. across and 1 foot down. So, that should mean that there is a block and a half going across and there are two blocks going down. That's the same for this one. Now I'll talk about the door. The door is 3 feet high, so it should be 6 blocks up, and 3 blocks across. Now the sideviews. Both of them have two windows, 1 foot going across and 1 foot going up. Also, I'd like to talk about the extra wood. The extra wood in the parenthesis means how many there is. It shows it right here, they're in the windows. Like this, there's four of them, it shows it right here. And then right here it can show that there are two of them, right here and right here (points to two window spaces), and then, like this big space, this is the door, it shows that it has one of these, and then the number tells the number of them so you can look right here at the parts that are extra wood and you can find where these are. Now I put important by this right here, I put the shutters, are 3 in. each, um, so the architect would know, um, how long to paint, um, how long to draw, um. Thank you. [moves out of range of camera]

Presenter 2: Hi, I am Michael Sircar and I'm here to talk to you about our front view and top view. Lets start off with our window, you can see that our window has been 9 in. wide and 1 foot long, on both. The reason we picked 9 in. is because, so children could stick out their heads and, and see out, see outside, and so they would not get their head stuck, and because, the requirement sheet said that any openings would have to be more wider than 7 in. Now, see our door. Our door has been 2 feet wide and 3 feet long. The reason we picked 2 feet wide is so that children wouldn't have to squeeze in, and the reason we picked 3 feet long is because so children wouldn't have to duck. Now you can see that our top view has been just four by four [picks up three dimensional scale model and orient top to audience]. You can see there has been grass, pencils, a school, and a flag. The way we got those extra pieces of wood has been from our 7 holes, One, 2, 3, 4, 5, 6, 7 [turns music stand to show audience each as he counts]. We got those extra pieces from our extra plywood, our grass, our pencils, the name of the school, and our flag. Thanks you [moves out of range of camera].

Presenter 3: Hi, my name is Mrs. Duncan, and y'all already met me today. Now, I'm going to talk about our left side, our right side of our school house. We have grass that is green and we have windows, and we got shutters from this extra credit, extra wood [points to blueprint]. And now I am going to talk about left side. We have grass that's green, we have extra wood again [points to blueprint where extra wood is detailed], and we have windows. Now I'm going to talk about why we built our school house. We built our school house for ages four and five year old children. They can play school, learn, and do all kinds of other things. Thank you [moves out of range of camera].

All in unison: [all three come back into camera view] Class dismissed.