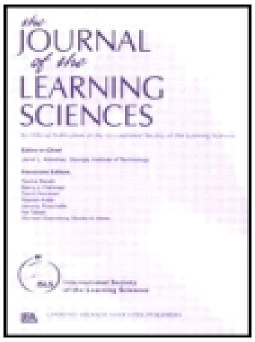

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Problem-Based Learning Meets Case-Based Reasoning in the Middle-School Science Classroom: Putting Learning by Design™ Into Practice[1]

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This article tells the story of the design of Learning by Design™ (LBD), a project-based inquiry approach to science learning with roots in case-based reasoning and problem-based learning, pointing out the theoretical contributions of both, classroom issues that arose upon piloting a first attempt, ways we addressed those challenges, lessons learned about promoting learning taking a project-based inquiry approach, and lessons learned about taking a theory-based approach to designing learning environments. LBD uses what we know about cognition to fashion a learning environment appropriate to deeply learning science concepts and skills and their applicability, in parallel with learning cognitive, social, learning, and communication skills. Our goal, in designing LBD, was to lay the foundation in middle school for students to be successful thinkers, learners, and decisionmakers throughout their lives and especially to help them begin to learn the science they need to know to thrive in the modern world. LBD has students learn science in the context of achieving design-and-build challenges. Included in LBD's framework is a set of ritualized and sequenced activities that help teachers and students acclimate to the culture of a

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[1] Timothy Koschmann served as the action editor for this article.

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highly collaborative, learner-centered, inquiry-oriented, and design-based classroom. Those ritualized activities help teachers and students learn the practices of scientists, engineers, and group members in ways that they can use outside the classroom. LBD is carefully crafted to promote deep and lasting learning, but we have learned that careful crafting is not enough for success in putting a collaborative inquiry approach into practice. Also essential are fostering a collaborative classroom culture in which students want to be engaged in deep learning and where the teacher sees herself as both a learner and a facilitator of learning, trusts that with her help the students can learn, and enthusiastically assumes the roles she needs to take on.

Too often, science instruction fails to engage students' interests and is divorced from their everyday experiences. Traditional science instruction has tended to exclude students who need to learn from contexts that are real-world, graspable, and self-evidently meaningful. At the same time, national curriculum reform efforts, including the American Association for the Advancement of Science's (AAAS, 1993) *Benchmarks for Science Literacy* and National Research Council's (NRC, 1996) *National Science Education Standards*, are suggesting that students should "do science" to gain "lasting knowledge and skills" in design, technology, and the sciences. There are also calls for students to learn complex cognitive, social, and communication skills as part of their middle- and high-school experiences to help them develop "habits of mind." In addition, there is a need for students to be learning science in ways that allow them to put it into practice solving problems and making decisions, rather than just warehousing collections of inert facts.

Our goal, which we took on in 1994, has been to use what we know about cognition (see, e.g., Bransford, Brown, & Cocking, 1999) to fashion a educational approach for middle-school science appropriate to deeply learning science concepts and skills and their applicability, in parallel with learning cognitive, social, learning, and communication skills. Our intention was that the approach would lay the foundation, in middle school, for students to be successful thinkers, learners, and decision makers throughout their lives, and especially to help them begin to learn the science they need to know to thrive in the modern world (Hmelo, Narayanan, Hubscher, Newstetter, & Kolodner, 1996; Kolodner, Hmelo, & Narayanan, 1996). We wanted to come up with an approach that could be adopted by a broad range of teachers and provide the full range of materials that would make such adoption possible.

The learning sciences community agrees that deep and effective learning is best promoted by situating learning in purposeful and engaging activity (see, e.g., Bransford et al., 1999; Collins, Brown, & Newman, 1989), and this is what we sought to accomplish. However, we wanted to go about it differently than other educational approaches. Our goal was to design an approach from scratch that would include everything the transfer literature had to say about promoting transferable learning (see, e.g., Bereiter, 1995; Bransford et al., 1999).

Our understanding of the model of learning from experience suggested by case-based reasoning (CBR; Kolodner, 1993; Schank, 1982, 1999) suggested to us that CBR provided a good model of the processes and knowledge representations required for transferable learning (Kolodner, Gray, & Fasse, 2003). Our intention was thus to try to promote science learning by promoting the kinds of reasoning suggested by CBR. We would have middle-school students engage in the kinds of experiences where they needed to use scientific knowledge and scientific reasoning skills to be successful. Then we would have them interpret their experiences in ways that CBR predicts would promote the ability to remember and reuse those experiences later.

However, although CBR could suggest the kinds of experiences and reasoning students should do to learn deeply, it did not tell us anything about classroom management, and we knew that to be successful, we would need to make sure what we were doing could work in classrooms. We therefore sought an approach to classroom practice compatible with CBR's suggestions. For this, we chose problem-based learning (PBL; Barrows, 1985; Koschmann, Myers, Feltovich, & Barrows, 1994), a cognitive apprenticeship approach that focuses on learning from problem-solving experience and promotes learning of content and practices at the same time.

As a first approach (Kolodner et al., 1996), we proposed that a merger of CBR and PBL would be the right starting point. Working along with talented teachers, we designed curriculum units and implemented this first approach in eighth-grade earth science and sixth- and seventh-grade life science classrooms (Gertzman & Kolodner, 1996; Hmelo, Holton, Allen, & Kolodner, 1996; Hmelo, Holton, & Kolodner, 2000). We identified many challenges to our conception. However, we believed the theoretical foundations we started from were powerful enough that we persevered, working to discover the specifics that would allow students to learn deeply and teachers to know how to manage the class and that would fit the constraints of middle-school classrooms.

Since then, our approach, called Learning by Design™ (LBD; Kolodner, 1997; Kolodner, Crismond, Gray, Holbrook, & Puntambekar, 1998; Kolodner et al., 2003), has been refined using a trial, analysis, and refinement approach (Linn & Songer, 1988) and has been evaluated with some two dozen teachers and 3,500 students, with good results (Holbrook, Gray, Fasse, Camp, & Kolodner, 2001; Kolodner et al., 2003). We have designed a set of units that cover a half year each of earth and physical sciences and that employ a set of practices that are meant to be applicable beyond those units. Our physical science units ask students to design and build a parachute (to learn about combining forces), to design and build a miniature car and its propulsion system so that it can go over several hills and beyond (to learn about forces and motion), and to design and build a device that can lift a heavy object for someone with a disability (to learn about mechanical advantage, work, and simple machines). Our earth science units ask students to design and model a way of managing the erosion on a big hill (to learn about earth's surface processes) and, acting as consultants, to make recommendations to civil engineers about the route, geological testing they need to do, and design of several underground transportation tunnels (to learn about rocks and minerals, underground water, map reading, and the rock cycle).[3]

We have had to address many practical issues in putting together a curriculum approach that can be broadly adopted—ways to make inquiry happen in the classroom despite the fact that teachers are not fully comfortable with it, ways of helping teachers learn facilitation skills on the job, ways to introduce a collaborative culture to the classroom, ways of making sure that teachers come to appreciate the importance of iteration and do not drop it from the sequence of activities in a curriculum unit, and so on.

This article focuses on the design of LBD—the process of going from a set of theoretical foundations to a workable classroom approach. We begin by presenting the theoretical foundations behind LBD, the practical issues (design challenges) we had to address to make LBD efficacious, the LBD approach that has arisen from those considerations, an overview of the major summative findings, and some lessons we have learned about designing a highly collaborative, learner-centered, inquiry-oriented, project-based curriculum approach.

GETTING STARTED ON DESIGNING A CLASSROOM APPROACH: LBD'S CONCEPTUAL FOUNDATIONS

Our goal was to address three issues head on—finding a way to engage nearly all learners, helping students learn important reasoning and social skills while learning content, and learning both content and skills well enough to be able to apply them in new situations (learning for transfer). We took many suggestions from the learning sciences literature.

Cognitive apprenticeship (Collins et al., 1989) suggested that learning focus on carrying out important skills in authentic contexts of use and that the content that needed to be learned could be learned in that context. It also suggested putting the teacher in the role of modeler and coach and articulator of process, gradually having students take over these roles. Reciprocal teaching (e.g., Brown & Palincsar, 1989; Palincsar & Brown, 1984) and PBL (e.g., Barrows, 1985) further suggested that a prescribed but adaptable sequence of classroom practices that engages students in targeted practices and skills and requires targeted knowledge for success should be

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[3] In this earth science unit, students design and build a variety of models (e.g., of sedimentary rock, of the flow of underground water) and use them to test ideas that come up during tunnel design, as building a full physical model of the tunnel area is infeasible. Discussing how we make earth science units work within Learning by Design™ is beyond the scope of this article, but an introduction to how we do it can be found in Camp, Gray, Groves, and Kolodner (2000).

designed. Goal-based scenarios (e.g., Schank, Fano, Bell, & Jona, 1994) suggested that learners take on a meaningful challenge and practice those skills and practices in the context of achieving the challenge. Project-based inquiry science (e.g., Blumenfeld et al., 1991; Edelson, Gordin, & Pea, 1999) suggested learning inquiry skills in the context of solving the kinds of real-world problems or addressing the kinds of big questions that experts might focus on. Anchored instruction (e.g., Barron et al., 1998; Cognition and Technology Group at Vanderbilt [CTGV], 1997, 1998), knowledge integration (Bell, Davis, & Linn, 1995; Linn, 1995), and cognitive flexibility theory (e.g., Spiro, Coulson, Feltovich, & Anderson, 1998; Spiro, Feltovich, Jackson, & Coulson, 1991) suggested that students engage in more than one challenge and with a wide variety of resources to learn targeted skills and knowledge—a wide enough variety that will allow them to learn the subtleties and richness of each targeted concept and skill. Constructionism (Harel & Papert, 1990; Kafai, 1996; Papert, 1991) suggested that learners engage in design challenges and that they have a personally meaningful physical artifact to take home with them and audience to share insights with while working on their designs. All of these approaches suggested that under these circumstances, learners could learn to ask important questions, carry out investigations, interpret data, and apply what they had learned. Fostering Communities of Learners (e.g., Brown & Campione, 1994) pointed out the importance of creating a culture in the classroom conducive to the kinds of collaboration that would promote peers being able to model, coach, and collaborate with each other and suggested that early activities should specifically target development of a classroom culture.

The transfer, analogical reasoning, expertise, and conceptual change literatures made further suggestions. The transfer literature tells us that learning for transfer entails

1. Learning skills and knowledge necessary to accomplish the initial task.
2. Ability to readily access those resources when a transfer opportunity is encountered.
3. Ability to recognize transfer opportunities.
4. Motivation to take advantage of transfer opportunities.
5. Ability to apply knowledge and skills flexibly (Marini & Genereux, 1995).

Successful transfer requires the knowledge and skills and the "disposition" (Bereiter, 1995) to use them fluently and without a great deal of deliberation, suggesting that not only do learners need deep understanding of the skills and when they are used but that they should experience their usefulness in ways that will promote that disposition. The literature (see, e.g., Bransford et al., 1999) reminds us that considerable time is needed for such learning, that learners need to feel accomplished along the way, that much time should be spent on "deliberate practice" (Ericsson, Krampe, & Tesch-Romer, 1993) that includes monitoring one's learning and experience of learning, that students should have the opportunity to see the transfer implications of what they are learning (Anderson, Reder, & Simon, 1996; Klahr & Carver, 1988), that they need to both experience the concreteness of particular problems and learn the abstractions and principles behind them (CTGV, 1997; Gick & Holyoak, 1983; Kolodner, 1997; Singley & Anderson, 1989), that before someone is ready to fully engage in transfer by himself or herself, he or she is often able to do the applicability and application part based on somebody else's prompting (e.g., Brown, Bransford, Ferrara, & Campione, 1983; Gick & Holyoak, 1980; Perfetto, Bransford, & Franks, 1983; Singley & Anderson, 1989), and that transfer can be improved by helping students become aware of the reasoning they are doing as they learn (Palincsar & Brown, 1984; Scardamalia, Bereiter, & Steinbach, 1984; Schoenfeld, 1983, 1985, 1991). Such practices engage students actively in focusing attention on critical issues, critical features of problems, and critical abstractions and principles and on evaluating their own understanding.

The scientific reasoning literature (e.g., Dagher, 1998; Greeno, 1992; Kuhn & Pearsall, 2000; Linn & Muilenburg, 1996; Mintzes, Wandersee, & Novak, 1998; Monk & Osborne, 2000; Zimmerman, 2000) and the literatures on setting up national science standards (AAAS, 1993; NRC, 1996) are rich in descriptions of scientific reasoning, suggesting reasoning skills we should have students learn, among them low-level skills like measuring and observation, and higher level skills like explanation and design of investigations. An essential part of this development of scientific reasoning skills includes learning to distinguish theory from opinion (Kuhn, 1997; Kuhn & Pearsall, 2000) and opinion from evidence (Zimmerman, 2000). These scientific reasoning skills, as well as skills for planning, communication, and independent learning, develop over time.

From these approaches come a variety of suggestions about engaging students, the skills and practices they need to learn, the framework to put them into so that they can learn skills and practices, and some roles of the teacher and experiences they should have. We wanted, however, to design an approach with far more specificity, especially about the sequencing of experiences and reasoning that would lead to transferable learning—something on the order of reciprocal teaching but focused on science learning in middle school. Reciprocal teaching was designed based on a model of the cognitive processing needed to be an expert reader (Bereiter & Scardamalia, 1987; Brown & Palincsar, 1989; Palincsar & Brown, 1984), and we thought we could get to the specificity we needed by finding a process-oriented model of the cognitive processes we wanted students to learn. We were not able to find a model specific to scientific reasoning, but we did have expertise in a particular process-oriented model of learning from experience—case-based reasoning (CBR; Kolodner, 1993; Schank, 1982, 1999). CBR was originally designed as a method for promoting machine intelligence and machine learning, inspired by the day-to-day reasoning we saw in people. CBR provided us with a powerful model of the cognition of learning from experience, suggesting the kinds of reasoning that would allow students to get the most from hands-on and project-based kinds of activities.

However, CBR had nothing to tell us about how to manage a classroom; for that, we made the decision to marry CBR to PBL. Both CBR, a constructivist model of learning, and PBL, an educational approach, situate learning in the activity of generating a solution in a real-world situation. Together, we thought, they pointed toward a mode of education in which one learns by extracting wisdom from one's experiences learning content and skills in such a way that they could be used flexibly in new situations.[4]

CBR

CBR (Kolodner, 1993; Schank, 1982, 1999) refers to reasoning based on previous experience (cases). That might mean solving a new problem by adapting an old solution or merging pieces of several old solutions, interpreting a new situation in light of similar situations, or projecting the effects of a new situation by examining the effects of a similar old situation.

A good example comes from architecture. An architect is designing an office building with a long, naturally lit atrium in the middle and a circular row of offices surrounding it. She wants the office to get as much light as possible so daytime energy consumption can be minimized. She remembers the design of a library that has no atrium but where the designer solved the problem of bringing in sunlight by constructing exterior walls of glass. She realizes that this solution can be used in the current building—the office space can be separated from the atrium by a circular glass wall. On further thought, she remembers the problems that a courthouse had, in which a glass wall was used in a row of offices with heavy public traffic. Although the offices were well lit, the constant presence of the public interfered with the privacy and work of the office workers. The library did not have this problem because the glass wall faced a wooded area.

Although the first case provides a means of dealing with her new design, the second case, and its difference from the first, alerts her to a potential problem with that solution. Comparing these two cases with the current one, she realizes that the potential for the problem exists, but to a lesser degree. Although the atrium is not deserted like the woods, it is not a heavily trafficked area either. She decides to use the first solution but modifies it slightly by using translucent glass bricks instead of clear plate glass for the wall.

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[4] We include rather detailed descriptions of both case-based reasoning and problem-based learning in this article, as there are a variety of subtleties in each that we have found important in our work that are not necessarily focused on in other presentations. We encourage those who are already familiar with case-based reasoning or problem-based learning, or both, to skim these sections rather than skip them.

This example mirrors much of the day-to-day reasoning we all do. For example, when someone plans a dinner party, he might first remember another dinner party he planned under similar circumstances (e.g., needed it to be easy to make, wanted to use summer vegetables) and consider whether its menu might be applicable to the new situation. If so, or if it is close, he adopts that menu modulo adaptations specific for the new situation (e.g., vegetarians are coming, requiring, perhaps, a second entrée).

Key to such reasoning is a memory that can access the right experiences (cases) at the times they are needed. We call this the *indexing problem*. CBR identifies two sets of procedures that allow such recognition to happen: (a) At insertion (encoding) time, while engaging in an experience, a reasoner interprets the situation and identifies at least some of the lessons it can teach and when those lessons might most productively be applied. The case is labeled according to its applicability conditions, that is, the circumstances in which it ought to be retrieved. The most discriminating labels on a case will be derived by a reasoner that has taken the time and effort and that has the background knowledge to carefully analyze a case's potential applicability. (b) At retrieval time, while engaging in a new situation, a reasoner uses his or her current goals and understanding of the new situation as a probe into memory, looking for cases that are usefully similar to the new one. The extent to which a reasoner is willing or able to interpret the new situation determines the quality of the probe into memory. An uninterpreted situation is likely to yield poorer access to the contents of memory than is one that is more embellished. The more creative a reasoner is at interpreting a situation, the more likely he or she is to find relevant knowledge and experience to use in reasoning about it.

Learning, in the CBR paradigm, means extending one's knowledge by interpreting new experiences and incorporating them into memory, by reinterpreting and reindexing old experiences to make them more usable and accessible, and by abstracting out generalizations over a set of experiences. Interpreting an experience means creating an explanation that connects one's goals and actions with resulting outcomes (e.g., the additional oregano in the tomato sauce was responsible for its enhanced flavor; the movement in the hallway distracted workers in windowed offices keeping them from getting their work done). Such learning depends heavily on the reasoner's ability to create such explanations, suggesting that the motivation, opportunity, and ability to explain are key to promoting learning.

CBR thus gives failure a central role in promoting learning because failure promotes a need to explain. When the reasoner's expectations fail, it is alerted that its knowledge or reasoning is deficient. When some outcome or solution is unsuccessful, the reasoner is similarly alerted to a deficiency in his or her knowledge. When such failures happen in the context of attempting to achieve a personally meaningful goal, the reasoner wants to explain so that he or she can be more successful. Crucial to recognizing and interpreting failure is useful feedback from the world. A reasoner that is connected to the world will be able to evaluate its solutions with respect to what results from them, allowing indexing that discriminates usability of old cases and allowing good judgments later about reuse.

Because one's first explanations might not be complete or accurate, CBR gives iterative refinement a central role as well. Central to CBR is the notion that we revise and refine our explanations (and thus, our knowledge) over time. We explain and index any experience the best we can at the time, and later on, when a similar situation comes up, we remember and try to apply what we learned from the past experience. We may find that we do not know how to apply it or we may apply something learned in an old situation and have it fail, each suggesting a need to revise what we know. We attempt to derive an explanation that covers both the old and new experience and revise our interpretation of the old experience as a result. The ability to accurately explain develops over time through noticing similarities and differences across diverse situations (e.g., Holyoak, 1984; Kolodner, 1993; Redmond, 1992). This research suggests that a variety of experiences with a concept or skill, personal ones and vicarious ones, are necessary to learn it to its full complexity.

CBR suggests a style of education in which students learn by engaging in problem solving and other activities that motivate the need to learn and that give students a chance to apply what is being learned in a way that affords real feedback (Kolodner, 1997; Kolodner et al., 1996; Schank & Cleary, 1994). In such an environment, students might engage in solving a series of real-world problems (e.g., managing erosion, planning for a tunnel, designing locker organizers), either for real or through realistic simulation, each requiring identification of issues that need resolution and knowledge that needs to be learned to address those issues, exploration or investigation or experimentation to learn the needed knowledge, application of that knowledge to solve the problem, and generation and assessment of a solution. Designing locker organizers, for example, requires students to understand the variety of ways lockers are used, other relevant storage subsystems, concepts of geometry, and concepts about physical structures, supports, and materials. They might engage in taking surveys and learn both math concepts (sampling, averaging, probabilities) and social sciences concepts (question asking) in the process. They learn concepts in geometry through drawing and manipulation of shapes. They learn physics concepts from consideration of the kinds of support structures their locker organizers need and so on. Participation in design and problem-solving activity, especially when students must make something work, gives them the opportunity to notice what they need to learn, experience the application of that knowledge, and learn how it is used.

In essence, CBR's model of cognition suggests that we set up learning environments such that there are clear affordances for having the kinds of experiences one can learn from and interpreting them in productive ways:

- CBR's focus on the role of failure in promoting learning suggests the importance of acquiring feedback on decisions made in order to be able to identify holes in one's knowledge and to generate goals for additional learning. CBR's approach emphasizes the need for students to actually carry out and test their ideas, not only think about them.
- CBR's focus on explanation suggests that the learners should be pushed to both predict and explain and that they should be helped to do both successfully. One cannot recognize a need to explain without first seeing a difference between what was expected and what happened. Thus prediction is important so that students can recognize holes in what they know.
- CBR's focus on indexing as the key to reuse of what's learned from experience suggests that in addition to having experiences students must reflect on and assess those experiences to extract both what might be learned from them and the circumstances under which those lessons might be appropriately applied to index their experiences well for reuse.
- CBR's focus on iterative refinement suggests that learners should have the opportunity to try out their ideas in a variety of situations and to cycle through application of what they are learning, interpretation of feedback, and explanation and revision of conceptions several times—that we should not expect one application to promote accurate learning.
- CBR's focus on the role previous experience plays in reasoning suggests that learners should be encouraged to reuse their own previous experiences as they solve "school" problems. It also suggests that they might be helped along to solve more complex problems than they could by themselves by having access to the cases (experiences) of others.

Focus on Design

CBR's suggestions imply that a particularly effective kind of activity for engaging in learning is designing working artifacts or devices. By designing, we refer to the full range of activities that a professional designer (e.g., engineer, architect, industrial designer) engages in to fully achieve a design challenge—understanding the challenge and the environment in which its solution must function well; generating ideas; learning new concepts necessary for its solution (through a variety of means, ranging from asking an expert to reading to carrying out an investigation); building models and testing them, analyzing, rethinking, and revising; and going back to any of the previous steps to move forward, repeating until a solution is found. Design as a vehicle for promoting learning has many affordances:

- Design challenges promote and focus learning, provide opportunities for application, and allow skill and concept learning.

- Students' construction failures are opportunities for testing and revising newly developing conceptions.
- Designing a working artifact naturally involves iterations in design; if done well, each can contribute to iterative refinement in understanding of concepts and gradual learning of skills and practices.
- Doing and reflection, aimed at helping students turn their experiences into accessible, reusable cases, can be easily interleaved with each other—students' want to successfully achieve a design challenge provides a natural motivation for discussing the rationale behind their own design decisions, for wanting to hear about the designs and rationales of others, for identifying what else they need to learn, and for wanting to learn the science concepts that will allow them to come up with better solutions.
- Designing affords learning of communication, representation, decision making, and collaboration skills—designers must show their design ideas to others and sell them.

Having students work on achieving design challenges, we thought, would naturally afford much of the orchestration suggested by CBR.

PBL

How should day-to-day activities and roles be managed in the classroom? Problem-based learning (PBL; Barrows, 1985), a cognitive–apprentice style (Collins et al., 1989) approach to educational practice, provided suggestions most consistent with CBR's predictions about promoting productive learning. In PBL, students learn by solving real-world problems and reflecting on their experiences; in medicine, this means diagnosing and managing patient cases. Because the problems are complex, students work together in groups where they pool their expertise and experience and together grapple with the complexities of the issues that must be considered. Coaches guide student reflection on their problem-solving experiences, asking students to articulate both the concepts and skills they are learning, and helping them identify the cognitive skills needed for problem solving, the full range of skills needed for collaboration and articulation, and the principles behind those skills. Students decide how to go about solving problems and what they need to learn, while coaches question students to force them to justify their approach and explain their conclusions. Students learn the practices of the profession they are learning, the content professionals need to know, as well as skills needed for life-long learning. PBL has been used substantially in medical and business schools (Barrows, 1985; Williams, 1992) for over 20 years. Research shows that students in problem-based curricula are indeed learning facts and concepts and the skills needed for critical problem solving and self-learning (Hmelo, 1995; Norman & Schmidt, 1992; Vu, Vander der Vleuten, & Lacombe, 1998).

PBL prescribes a structured sequence of classroom practices. Students work as a group to record on a specially formatted whiteboard the facts they know, hypotheses and ideas they have about explaining and solving the problem, and issues they do not yet understand and need to learn more about (learning issues). After considering the case with their existing knowledge, students divide up the learning issues they have generated among the group and investigate them. When they get back together, they return to their problem-solving activity, this time using what they have learned from investigation to move further forward in their solutions. They reconsider their hypotheses, generate new hypotheses, and generate new learning issues in light of their new learning. This cycle continues until students are satisfied that they have solved the problem and that they sufficiently understand the learning issues they have identified.

Reflection and abstraction play key roles in the PBL classroom. Coaches are taught to continually prompt students to explain their hypotheses and ideas. Each time an entry is put on the whiteboard, the coach attempts to have students give as good an explanation as they can of why they are proposing their idea or why they need to learn a proposed concept or process. The explanations from those discussions are articulated on the whiteboards, which soon fill up with concept maps, diagrams of processes, and explanations. This in-process reflection helps students make connections between their problem-solving goals, the processes involved in achieving those goals, and the content they are learning, and helps them abstract out processes and explanations that apply beyond the problem they are working on. It pushes them to consider how they are applying what they know and what they are learning. Writing down those explanations publicly promotes making conceptions explicit, comparisons between the conceptions of different students, and discussions of those differences.

Coaches also prompt students to discuss the kinds of resources they will employ as they investigate their learning issues. They might look things up in books, talk to experts, run experiments, or investigate in other ways. Each student must say what they are planning to do before leaving to carry out their investigation. On returning from investigating, the first discussion (before returning to the problem to be solved) is about use of resources and strategies for investigation. What strategies and resources did students use successfully? Which ones might they need more practice with? What strategies did they abandon and why?

On completion of solving a problem, students compare and contrast their own solutions with those of experts, identifying the differences between their solutions, the reasoning the experts did, and the differences between the experts' reasoning and that of the students. This might result in additional learning issues being identified and investigated.

Several key practices stand out in PBL. First, it is a continuous, ongoing approach to learning. The cycle of practices are carried out over and over again in the context of a solving a whole series of problems (100 is typical in the first 2 years of medical school). The well-articulated and consistently repeated sequence of practices allows learners to get used to a framework for learning and then to manage within that framework. It provides them a way of identifying the practices they need to learn and of observing their increasing abilities to carry out those practices. Barrows (1985) told us that this consistent framework is critical to setting the expectations of the students and helping them learn how to learn. The expectation, among students and teachers, is that learners' ability to solve problems and learn from them will grow in parallel with their content knowledge. Thus, there is not a need to learn everything that a particular problem affords; there will always be other opportunities to grow skills and to learn and use the content.

Second, the specially formatted whiteboard, as a public repository of what the students know, their ideas, and what they need to learn, allows a group of students working together to move forward together in solving a problem and to explicitly keep track of their progress over time. In addition, it encourages articulation, identification of, and discussion of conceptions and misconceptions—in the context of a need to know and understand.

Third, the reflection and abstraction done in a PBL environment take advantage of the full range of learning opportunities that present themselves when learning in the context of problem solving. Learning about concepts, learning practices of a community of experts, and learning practices involved in learning are all the focus of reflection or abstraction at different times. Learning in a context of problem solving can be quite overwhelming; there is much going on and many different things might be learned or overlooked. Scheduling times for all the different kinds of reflection and abstraction insures that the most important learning opportunities will be recognized and taken advantage of.

PRACTICAL CONSTRAINTS AND CORE CHALLENGES IN DESIGNING A CLASSROOM METHODOLOGY FOR MIDDLE SCHOOL

The framework presented previously has many good principles for promoting transferable learning, but we learned during our early attempts at implementation that it was not yet specific enough to work in a middle-school classroom (Gertzman & Kolodner, 1996; Hmelo et al., 2000; Hmelo, Narayanan, et al., 1996). Middle-school students do not come to school ready to take on challenges, as career-minded medical students and business-school students do. As well, they are not yet good at having an informed dialog, and they do not know how to organize themselves to solve a big problem. They do not yet appreciate the need to make connections between what they know and what they are encountering. Because of their naive level of knowledge and metacognitive skills, middle schoolers are in greater need of scaffolding than are students in professional schools. In most states, middle-school teachers do not have extensive subject knowledge or strong science-methodology skills (Ingersoll & Gruber, 1996) that they can use to help students. We had a need, as well, to adapt PBL to design and to middle school. We discovered that we needed to more clearly specify what makes for a good design challenge and create sequences of activities that would keep students focused on the science. In addition, we needed to learn how to deal with other characteristics of the middle-school environment—length of classes, available workspace, available materials and tools, expectations about coverage of content, and interruptions (e.g., assemblies)—that constrain what is possible.

Our challenges, we found, fell into three categories:

1. Iteration, sequencing, and orchestration.
2. Getting to the science.
3. Getting to a classroom culture.

We had to design solutions to these challenges that helped teachers as well as students acclimate to new kinds of activities in the classroom.

Iteration, Sequencing, and Orchestration Challenges

We had a number of challenges in this category. First, PBL tells us how a single teacher can interact with a group of 7 or 8 students but not how to manage a classroom of 30 or 35 students. One way that PBL has been used in middle schools and high school is to have the class of 30 students like a class of 7 or 8, discussing all issues with the entire class and sending students out as individuals to investigate and report back. However, the logistics of making sure all students remain engaged would be difficult, we thought, in this way of practice, and we thought that this approach failed to take advantage of the social affordances inherent in the classroom. We thought it would be better to have students work in small groups on the kinds of things that PBL has individuals work on (e.g., investigation).

Once we decided that, we also had to worry about helping groups of students stay on track and making sure that no groups were falling behind. To achieve that, we introduced into the sequencing a framework of interweaving small-group and whole-class activities. We asked teachers to bring the class together as a group each time they need to prepare for a new activity, after investigations, after design planning, and several times during design. During whole-class time, students would present to each other, the teacher would help students see similarities across what the different groups were doing and pull out science concepts, the class whiteboard would be revisited and revised, and the teacher would help prepare students for what they would be doing in their small groups. We also created paper-and-pencil scaffolding in the form of Design Diaries (Puntambekar & Kolodner, 1998) to provide prompting while students were working in small groups (Figures 4 through 6 show three of our most successful Design Diary pages). In addition, we asked teachers to travel from group to group as students were working and provide help as needed.

Second, we needed to learn how to help teachers balance time between investigation and iterative design (Hmelo et al., 2000), on the one hand, and between doing and interpretive and reflective activities on the other hand. Left to their own devices, we found that teachers focused on the familiar—organizing class so that there was plenty of time for students to engage in investigation, but leaving little or no time for iteration, application, and discussions of what was being learned (Gertzman & Kolodner, 1996; Hmelo et al., 2000). Students did not learn as much as we had hoped in these circumstances. We found the same thing when we looked at teachers' natural inclination to promote reflective activities among the students. They often allowed so much time for construction that there was little time for reflection after, and when they did leave time for reflection, they often hurried through because of their unfamiliarity with helping students extract from their experiences what they had learned. To address these issues, we had to make sure that construction activities would not be too time consuming (more on that next), we had to find ways to sequence activities so that there was time available for iteration, and we carefully crafted several kinds of presentation and whole-class discussion activities that each required focus on different sets of issues. By naming and "ritualizing" those activities, inserting each into the sequencing where it belonged, and helping teachers and students learn their scripts early on, we thought we would be able to help both teachers and students know what interpretations and reflections were appropriate at different times in the project sequencing (more on this next as well).

Third, PBL's initial inquiry (getting started) needed to be managed differently for design challenges than for the diagnostic activities it was created for. During initial inquiry, learners are expected to ask the kinds of questions that will allow them to understand the constellation of problems they need to address to solve their problem-solving challenge. However, doing that depends on students having some idea of what kinds of issues they need to address and on answers being available. We cannot depend on middle-school students to know what to ask. Students have little experience with construction and tinkering, and they have little idea about how things work. Initial inquiry, in the design classroom, needs to help students try to discern how and why things work so they can begin to identify what they need to learn more about (and so they can begin to develop excitement about the challenge). We found that we needed to get students involved early on in trying to make something work or in comparing and contrasting how available devices work to help them identify the issues ("problems" in PBL terminology) that they needed to address to successfully achieve the challenge (Hmelo et al., 2000). We inserted "messing about" with devices or materials into LBD's sequencing to come before the first whiteboarding session for this purpose.

Fourth, we needed to help teachers orchestrate activities in the classroom so that they could assess the progress of individuals. We wanted students to work as teams because we believe they can learn more deeply that way. On the other hand, our teachers needed to be able to give individual grades, and the students needed to know that there are consequences to sloughing off. Our solution to this has been to designate homework (and tests, if the teachers give them) as the venue for individual work and to aim for two types of homework assignments: (a) nightly homework assignments that will prepare them for their group work the next day or ask them to reflect on and articulate what they did or learned in a group activity, and (b) longer term reports that ask them to write up their group experience as individuals. Included in the first set of assignments are things like interpreting the results of an experiment and using the results of experiments to propose a design, justifying each proposed idea (e.g., lab reports after experiments are designed and run, product histories detailing the way the challenge was addressed and what was learned from it, and individual transfer tasks—applying what was learned to a new situation).

Connecting Design Activities to Science Content

Construction activities, we found, can quickly turn into arts and crafts activities (Hmelo et al., 2000), where students and teachers focus on getting to a working solution by trial and error and forget to connect the construction activity to the targeted science. In part, this is because many middle-school teachers do not know the science they are teaching; partly, it is because they have not been taught to recognize the uses and manifestations of science in the world around them. This makes it difficult for them to recognize the opportunities for connecting science to construction activities. At the same time, students who had no experience with tools and materials had trouble even getting started with making something work. In addition, when teachers are short on time and students have spent considerable time constructing, they tended to quickly gloss over the science. There are several challenges here: (a) choosing the kinds of design projects that clearly benefit from scientific understanding, (b) providing students with enough project expertise so that they can be successful enough at project activities to be successful at constructing the devices they designed, (c) making the construction activities short enough so that there is time for both construction and science discussion, (d) and making the connections between the science and the content explicit enough so that both teachers and students can see them.

We addressed these challenges in three ways. First, we revised the initial focus on design to create instead a "redesign" approach (Crismond, 1997). By providing instructions for building a modestly working device and having students identify changes they needed to make in the design to get to a well-working device, we thought we could help teachers and students direct their focus to design details that depend on scientific understanding for their best implementations. We thought that a way to get the right kinds of questions on the whiteboard, even if the teacher did not know science well or was not a strong facilitator of inquiry, would be to have groups build a first version and then have them share what happened. The experience of trying to make their device do what it needed to do would encourage students to ask questions about how to make it work better—questions that would require science understanding to generate answers. For example, if their first version of a vehicle could not make it over a hill, at least some students in the class would want to find out how to give it the power to get over the hill, and the need to understand how forces cause changes in motion would be uncovered.

Second, we specialized the sequencing of the PBL cycle:

1. Initial construction, testing, and attempts to explain the workings of constructed devices, followed by
2. Investigation of the effects of changing attributes of the design (one at a time), resulting in articulation of design "rules of thumb," followed by
3. Redesign of the device that brings together the results of the whole set of investigations, and finally
4. Iterative construction, testing, and redesign toward their best-working device (see Figure 1).

Putting this cycle in place allowed us to become specific about the kinds of presentations groups would make to each other during times when the class met as a whole and the focus of class discussions after those presentations. Discussions after the first attempt would be around a whiteboard and result in identifying issues needing investigation (learning issues in PBL parlance); presentations after investigations would focus on investigational methodology, data collected, and interpre-

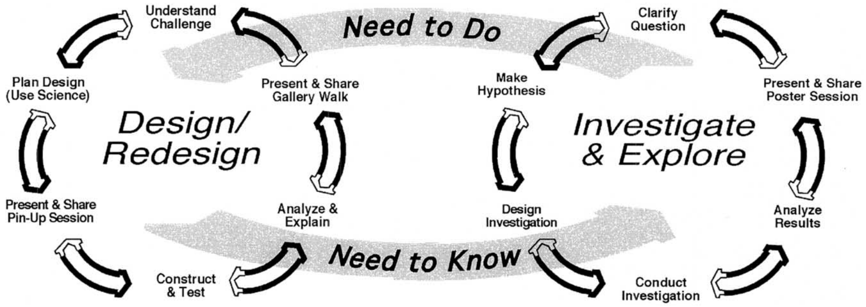


FIGURE 1 The Learning by Design Cycle. From "Promoting Transfer Through Case-Based Reasoning: Rituals and Practices in Learning by Design Classrooms," by J. Kolodner, J. Gray, and B. Fasse, 2003, *Cognitive Science Quarterly, 3*. Reprinted with permission.

tation of results, and discussions following those would focus on methodology as well as on trying to explain the results scientifically; the next set of presentations would focus on design ideas, and discussion following those would focus on using experimental results and scientific understanding to justify decisions; and presentations during iterative construction and testing would focus on what happened when scientific principles were put into practice, with discussions focused on helping students explain their results scientifically and deepen their understanding.

Trends derived from investigations, articulated as design “rules of thumb,” we thought, would propel these discussions forward and connect them to each other. Design rules of thumb (e.g., “If you want the car to travel farther, decrease its mass because the same force can propel something light farther than something heavy”) can provide connections between observed phenomena and scientific principles, especially if they are revisited frequently to try to explain them and to assign applicability conditions. Rules of thumb were to be proposed based on experiments, with a first attempt at explaining them coming during discussions following investigations. They were to be revisited as students worked on their design ideas and revised as students applied them during construction and found that they were not yet fully explained.

Finally, to facilitate fluid use of rules of thumb and to remind students of their usefulness and centrality, we asked teachers to display the class’ list of design “rules of thumb” in the classroom and to revisit it often, especially to fill in conditions of applicability and explanations as they were discovered.

Creating a Classroom Culture and Ethos

Essential to any learner-centered approach is a culture of collaboration and interdependence (Brown & Campione, 1994). Essential to learning from design activities is a culture of iteration. Essential to learning science practices is a culture of scientific reasoning. In a culture of collaboration and interdependence, every member of the community feels responsibility towards helping others learn, and every member of the community knows that he or she can depend on others for help when needed. In a culture of iteration, members of a community expect that they need to fail and explain to finally understand well and succeed. In a culture of scientific reasoning, members of the community use causality and scientific principles in their explanations and cite evidence they and others have collected. This is a far cry from what teachers and students are used to. It is difficult for students to differentiate between collaboration and cheating and between failure that you can learn from and failure, and it is difficult for them to get to a point where they can appreciate that they can learn from each other and that the teacher does not have all the answers.

We tried to address these challenges in two ways. First, we created “launcher” units to introduce important science, design, and collaboration practices. The launcher units (Holbrook & Kolodner, 2000) provide students with experiences engaging in science, design, and collaboration practices and with watching professionals do the same. In our physical science launcher, for example, students watch the movie *Apollo 13* and then discuss the many things scientists were doing in the context of sending the Apollo spacecraft into space and saving the men's lives when the mission was endangered. Students engage in those same kinds of activities—collaborating, investigating an unknown, making a well-formed scientific argument, designing an experiment, and so on. Activities are interleaved with discussions that focus on the practices they are carrying out and what makes them successful. The launcher units also provide an opportunity for putting in place a collaborative classroom culture. Students almost always begin the year resistant to collaboration and expecting the teacher to always tell them what to do (Gertzman & Kolodner, 1996). The launcher units are designed to help students become a community, to take on more independence in a nonthreatening way, and to experience what the norms of the classroom would be for the remainder of the year. They are also designed to provide the teacher with time to ease into their new practices as modelers, coaches, and facilitators.

Our second approach was to "ritualize" activities and sequences of activities. Ritualizing, to us, means defining the sequence of events for some activity in such a way that students and teacher would come to be able to effortlessly engage in it. In effect, ritualizing makes the expectations for any activity clear and succinct. Within LBD, a group plans, then runs, then reports on its experiments. When planning an experiment, they begin by focusing on which variable to vary and how to keep others constant. When reporting on the experiment, one explains the procedure, being careful to talk about how one made sure to keep variables constant, and so on, and one tries to extract a design rule of thumb that others will find useful later on when they design. Some of LBD's rituals are consistent with the practices of scientists (e.g., running and reporting on experiments), others are consistent with what designers do (e.g., explaining and justifying one's design decisions to others), and others are adaptations of learning activities done in architecture design studios (e.g., presenting one's solution in progress). By ritualizing the activities and sequences of activities, much as PBL's sequence does, we thought we could help teachers and students learn what their roles needed to be at different times.

LBD'S MACRO AND MICROLEVELS

We eventually converged on a cycling of activities (see Figure 1) that seems to provide the affordances CBR suggests are needed, that addresses the challenges suggested by early LBD implementations and that is consistent with the suggestions made by the learning and transfer literatures.

In the typical sequence of activities in our current (2002) Learning-by-Design units, students begin by encountering a design challenge that they are asked to achieve. To help them understand the ins and outs of the challenge and identify what they need to learn more about to successfully achieve it (initial inquiry in PBL lingo), we help them to explore the materials and environment in which the challenge must be achieved by "messing about" (Hawkins, 1974) with construction materials or with objects in the challenge environment to see what their constraints and affordances are. The teacher might also present demonstrations that engage students in those same sets of issues or ask the students to read something short. Later, in whole-class discussions around the whiteboard, the teacher helps students articulate what they learned while messing about, generate a better description of what they need to achieve, generate ideas for how to achieve the challenge, compare and contrast their ideas, and identify what they need to learn to move forward in addressing the design challenge. This discussion provides an opportunity for the teacher to identify student misunderstandings and misconceptions and to begin the process of helping students move toward more complete and correct conceptions.

Following this are cycles of investigation and application. A set of "learning issues" that focus on a scientific area is chosen for investigation. Each group in the class is assigned one of those learning issues and designs and runs an investigation to try to understand it better and then reports their findings to the class. This is followed by trying to apply what was learned to the challenge. Potential solutions to the design challenge are attempted in each cycle and evaluated by building and testing a model or actual device, comparing different design alternatives based on qualitative or quantitative understandings, or analyzing using established design guidelines or the ratings of experts. Presentations and discussions following each cycle focus on what has been tried, what has been learned, how to apply what has been learned, explaining things that did not work as well as expected, and identifying what else still needs to be learned. The cycle is continued taking a new set of learning issues into account.

The Macrolevel

The macrolevel of activities that carries out all of these essential principles of practice is shown in Figure 1. The figure shows two essential components of learning from design activities—design and redesign (including project activities and application) and investigation. Tucked within each of these components are a variety of doing and reflective activities and public presentations aimed at helping students interpret their experiences in ways that will allow them to identify what they are learning and connect their actions with their goals—what CBR says is important for promoting deep and lasting learning. Together, the two specialize a learning cycle, where the steps in the learning cycle are enacted through activities specific to investigating and designing.

Design and redesign (Figure 2) grounds the sequencing of activities in LBD. Students begin with a challenge. To make progress in achieving it, they need to understand it—doing whatever activities are required to identify its criteria and constraints (what needs to be achieved and under what limitations) and the problems that need to be addressed and carrying out investigations, explorations, or reading to learn more. This step is where PBL-type whiteboarding is done. They continue by using what they know to generate or refine their ideas for addressing the challenge (we refer to this as design planning). This is followed by more investigation if new issues are identified that need investigation or sharing their ideas with the class in a pin-up session, making predictions about how their designed artifact will behave, and, for each design decision they have made, providing evidence to justify it. After idea sharing, in a pin-up session, they refine their ideas and move on to constructing and testing their artifact, running fair tests to collect data about its behavior and capabilities. More often than not, early versions of their designed artifacts fail to behave as predicted, and students must analyze their data and the ob-

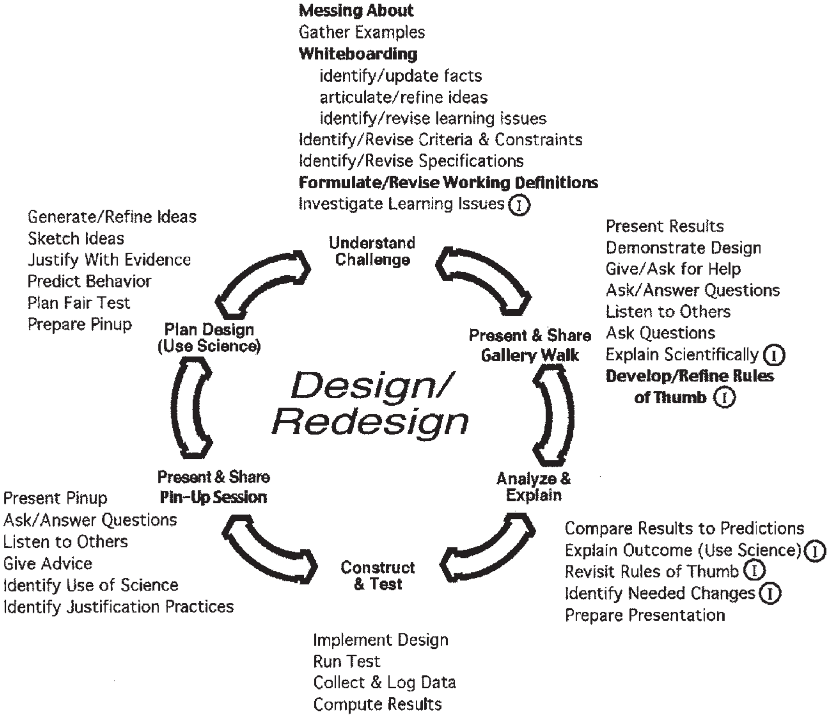


FIGURE 2 Design and redesign.

servations they have made and explain why it worked the way it did and what else they might need to learn more about. This is followed by another presentation session, a gallery walk, this time with presentations of design experiences and requests from peers to help with explanation and with deciding how to move forward. The cycle repeats taking these explanations into account.

Three aspects of this cycle are important to notice. First, students do not just think through to solutions, they actually build artifacts and try to make them work. As we stated earlier, getting timely and concrete feedback from the world helps in recognizing that one's conceptions are faulty. Of course, a device might not work because of poor construction rather than because of a poor scientific conception. The explanatory part of this cycle is for figuring that out. Because middle-school students are not always good at explaining, because scientific explanation is a skill we want them to learn, and because they often do not know enough yet to explain well, public presentation of design experiences is critical to the cycle as well.

This is the second aspect of the cycle to notice. The design–redesign cycle includes two kinds of presentations as critical components—presentation of design ideas in the pin-up session and presentation of design experiences in the gallery walk. In the pin-up session, students present their design ideas and the reasoning behind each, including the evidence they used while reasoning. This is to help them learn to make informed decisions and to justify choices based on evidence. In the gallery walk, they present their design experiences to each other. This is the venue for presenting to each other their explanations of why their devices worked the way they did or did not work the way they expected, for asking for help from their peers if they cannot explain, and for identifying additional things they need to learn about. Such public presentations are important for a number of reasons—as a prompt for putting one's thoughts in order and as a way of getting feedback, among others. The active listening that others do during presentations is important for other reasons—getting ideas, getting experience with alternative perspectives, and so on. Presentation provides a door into reflection and abstraction, critical components of learning from project activities. Right after presentations is an excellent time for the teacher to help students see commonalities across the experiences of different groups in the class and to help them extract and refine scientific principles.

Finally, we expect students to go through many cycles of redesign (we call each an iteration) for each challenge they are addressing, mediated by presentation to and feedback from the class and additional investigation. Testing a design and finding it lacking might send a designer back to better understand the design challenge or to do further investigations into some issues. Students cycle through this set of activities until they have achieved the challenge in a satisfactory way.

Investigation (see Figure 3) is called on as a natural response to learning issues generated while trying to understand a challenge, explain a result, or decide how to proceed with a redesign. Learning issues may be about science, design, or con-

FIGURE 3 Investigate and explore.

struction. Investigation can take a variety of forms, including reading, modeling, talking to an expert, examining cases, analyzing demonstrations, or experimenting. We provide texts to students explaining scientific concepts and skills and some technological concepts and skills, but we do not believe they can really understand those until after they have experienced a phenomena. Thus, we ask teachers to have students investigate actively, through simulation or modeling, or through designing and running experiments, to find things out before reading. Investigation may be returned to over and over. Construction and testing may show something does not work, calling one's understanding into question. Additional questions are generated, and additional investigations might be warranted.

Looking at Figure 3, one sees a cycle of activities that make up an inquiry cycle. One begins by clarifying the question to be addressed, stating it in such a way that it can be addressed successfully in an investigation, and then one makes a hypothesis. Designing the investigation refers to designating the procedure. For experimentation, this includes identifying conditions that need to be controlled, the variable that will be varied and its values, steps to be carried out, number of trials, what to measure, and so forth. For modeling, students need to design the model and identify how it will be run to collect data to answer their question. For case interpretation, they need to identify what they will be looking for as they read a case. This is followed by investigation and recording of data, analysis of results, and presentation of results in a poster session. To help students identify whether their results are believable, we ask them to try to identify design rules of thumb that they can recommend to their peers based on their experimental procedure and results.

Important to notice here are three things that are special to LBD's inquiry cycle and that we think are key to LBD's success. First, as in any good inquiry approach, students design and run their own experiments to address learning issues. The whiteboarding session before experiments are designed is the venue the teacher uses to help the class turn their questions into learning issues that can be investigated easily. It also serves as a public forum where the teacher can model, and then gradually hand over to students, the skills involved in generating a good question for investigation. Second, investigation is distributed around the classroom, with each group taking on investigation of one of the learning issues identified by the class and then presenting to their peers. This distribution has resulted in students becoming quite interested in the results their peers are generating, as they need those results to achieve the challenge well. They are thus motivated to ask each other questions about their procedures. Discussion of scientific methodology seems to spring naturally from this setup. Finally, the poster session, LBD's public presentation of experimental design and results, is a fundamental part of the cycle. As in the scientific world, students come to understand that peer acceptance of their procedures and results is critical to moving understanding forward. Presentation, as well, forces students to put their thoughts in order—to do much of the reflection on their experiences that CBR tells us are important for turning one's experiences into well-articulated cases in one's memory.

The Microlevel Rituals in More Detail

Within LBD's two macrophases lay many small practical implementation details, some of which have been alluded to previously. We conceive of LBD's repeated activity structures as "ritualized activity structures" or "rituals" (Kolodner & Gray, 2002). There are two kinds of ritualized activities in LBD: small-group rituals and community rituals. Students work in small groups to explore, investigate, apply what they are learning, explain, justify, and prepare reports to the class. They gather together as a classroom community to share experiences, learn from, listen to and advise each other; to refine their understanding of the challenge, of science concepts, and of science and project practices together; and to plan. PBL tells us that the more familiar students are with the activities they are engaging in, the more fluidly they will be able to engage in them. This is the reasoning behind our ritualizing of the activities that students engage in repetitively from cycle to cycle and project to project. Ritualizing the practices systematizes them to make them methodical and encourages good habits and introduces practices in context of purposeful use. Engaging in community rituals has students engage in practices in public along with a community of collaborators, thereby affording noticing, asking clarifying questions, suggesting, comparison across exemplars, and reflective discussion aimed at productive interpretation of what they are doing and learning.

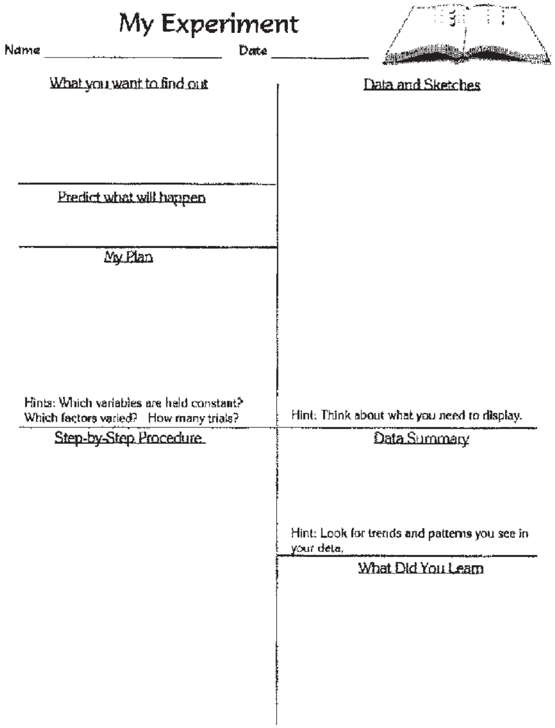
Small-group rituals are those that small groups engage in as they are exploring, investigating, designing, constructing, and getting ready for presentations. Small-group rituals tend to ritualize, at a level that middle-school students can handle, the kinds of practices that scientists and engineers typically engage in.

Messing about (see Figure 2), for example, is a playful exploratory activity where students construct a modestly working device of the kind they will be redesigning later and tinker with it to discover its capabilities and ways of making it better, explore the characteristics of materials they will be using, or play with and explore devices like those they will be designing to see what their capabilities are and what effects how well they work. The goals of messing about are to get students intellectually engaged with the challenge they will be addressing and at the same time prompt them to ask the kinds of questions whose answers will help them understand science content better and help them achieve the stated challenge. During *Vehicles in Motion*, for example, a unit where students learn about motion and forces by designing and redesigning a miniature vehicle and its propulsion system, students begin by examining the capabilities of toy cars they bring from home. Some can get over hills; some cannot. Some go long distances, some shorter. Exploring what each can do, and comparing and contrasting their features and mechanisms, allows students to begin asking questions about what it takes to make something go and to imagine what some of the answers might be. Later on, when they are getting at the details of producing propulsion, they explore the differences between different balloon-propulsion systems, getting ideas about the effects of different propulsion system features on performance, and identifying variables whose effects they need to learn more about through experimentation. Messing about is an informal exploratory activity where ideas and questions are generated. We ask students to observe what is happening and write it down and to try to explain, and we provide them with specific guidelines for each messing about session about what they might focus on. During class, as a group, they observe and write down observations. For homework, they might try to explain and classify what they have seen in preparation for the next day's whiteboarding session.

Designing an experiment is another small-group ritual, as is *running an experiment* and *preparing for a poster session* (Figure 3). Designing an experiment, as one might expect, includes writing down the group's question; making an informed prediction (hypothesis) about what the answer is; then specifying the objects to be tested, the conditions on those objects that need to be controlled, the variable that will be varied, the values it will have, the procedure that will be used, the conditions on that procedure that must be controlled, and the number of trials for each value of the variable; and then writing out steps in the procedure. To help, students use Design Diary pages that help them keep track of what they need to be considering as well as text about "Fair Testing" to help them judge whether the procedures they are coming up with are fair. Figure 4 shows the Design Diary page used while designing and then running experiments. Preparing for a poster session includes, among other things, trying to extract a rule of thumb from the data (under such and such conditions, expect such and such to happen, or the <smaller, larger> some characteristic, the <smaller, larger> some resulting condition). We present more about rules of thumb next.

Another investigative ritual students might engage in is *reading and learning from an expert case*. They read the case, first, to extract what the challenge was that the experts were addressing, what issues they had to contend with, and their constraints and criteria; the solution they came up with and why and which parts of the challenge it addressed; what happened as a result; and the science they used to achieve their challenge and how they applied it. They then look at the similarities and differences between the expert challenge and their challenge and judge whether the solution the experts used and the science they applied is applicable and how. Figure 5 shows the Design Diary page that students use to keep track of what they have learned from cases.

Fair testing is also an important part of *testing a design* (see Figure 2). Testing a design is a group ritual where what the group has built is put to the test. Usually,



My Experiment

Name ____________ Date ________

What you want to find out

Data and Sketches

Predict what will happen

My Plan

Hints: Which variables are held constant? Which factors varied? How many trials?

Hint: Think about what you need to display.

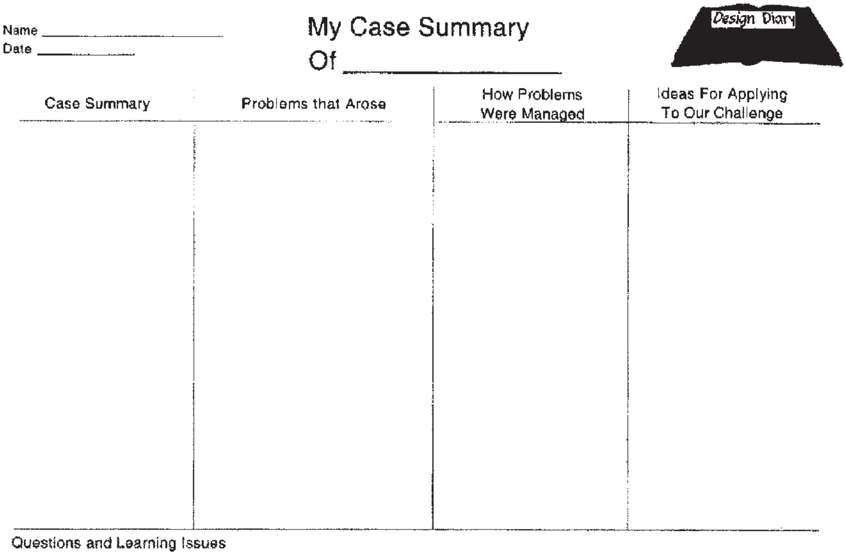
Step-by-Step Procedure

Data Summary

Hint: Look for trends and patterns you see in your data.

What Did You Learn

FIGURE 4 Design Diary page—My Experiment.



Name ____________
Date ________

My Case Summary
Of ____________

Design Diary

Case Summary	Problems that Arose	How Problems Were Managed	Ideas For Applying To Our Challenge

Questions and Learning Issues

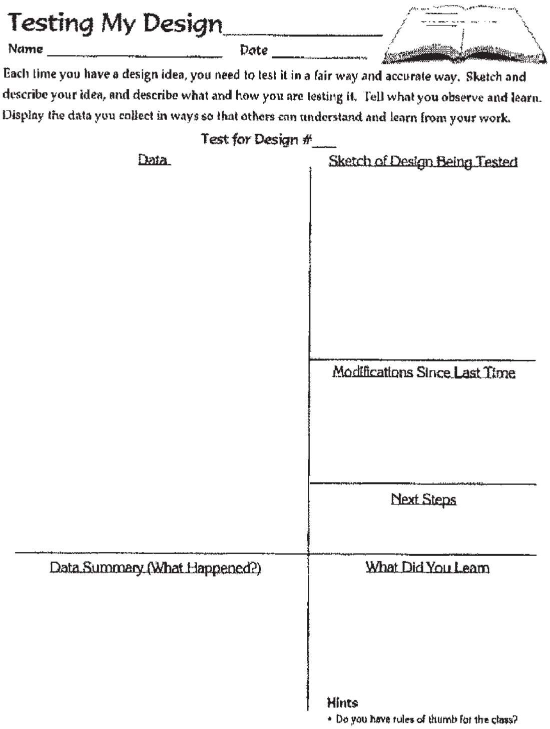
FIGURE 5 Design Diary page: My Case Summary.

students in the group divide up the work of testing. One gets the device started, another measures, another observes, another records, and so on. Figure 6 shows the design diary page they use while testing their designs.

Community rituals are designed to help students, as a community of learners, get the most from their experiences and to compensate for what they might not be able to accomplish in small groups without a full-time facilitator available—explain why things happened the way they did, identify science in action, identify the practices they are engaging in and how to perform them well, apply what they are learning, recognize what they do not understand, and so on. Community rituals are done as a whole class, facilitated by the teacher, and they usually come after some small-group activity and include or come after public presentation.

Whiteboarding (see Figures 2 and 3), for example, is almost exactly as in PBL. For each unit, the class first visits the whiteboard after messing about, and then they return to it and revise it each time they can answer some of the questions on it and each time they have new questions or ideas to add. Good use of the whiteboard helps students to see that indeed they are generating what they need to learn, helps them to see their learning progress, and helps them to keep in mind the big picture of what they are doing—why they are doing each of a unit's component pieces.

A major issue in science education is connecting observations in the real world with scientific principles and laws. LBD promotes making that connection through *generation and refinement of design rules of thumb* (see Figures 2 and 3). As stated previously, a *rule of thumb* is a guideline specifying the conditions under which some



Testing My Design_______________

Name ____________________ Date __________

Each time you have a design idea, you need to test it in a fair way and accurate way. Sketch and describe your idea, and describe what and how you are testing it. Tell what you observe and learn. Display the data you collect in ways so that others can understand and learn from your work.

Test for Design #___

Data

Sketch of Design Being Tested

Modifications Since Last Time

Next Steps

Data Summary (What Happened?)

What Did You Learn

Hints

- Do you have rules of thumb for the class?

FIGURE 6 Design Diary Page: Testing My Design.

behavior might happen or be appropriate (e.g., to keep dirt from moving, plant something with roots in it; to decrease friction, use bearings with a smooth surface). It is quite easy to generate rules of thumb from observations made during messing about or from results of experiments, and we ask students to try to generate rules of thumb while they are working in small groups to interpret their experimental results. However, it is harder to get the applicability conditions of a rule of thumb exactly right and to understand the science behind why it works. This is why we have made generation and refinement of design rules of thumb a community ritual. The ritual of generating rules of thumb includes guidelines for when to generate them (as the end product of an experiment) as well as for when to revisit them (when planning to achieve a design challenge), and when to refine them and explain them better (after attempting to use a rule of thumb in a constructed design or after seeing an example that shows the rule is too general or too specific). Revisiting a rule of thumb after trying to use it may call it into question, often promoting a need to investigate the science behind it to be able to use it more effectively.

For example, during *Vehicles in Motion*, classes typically generate a rule of thumb that says a vehicle will go farther if its wheel surfaces and bearings have low friction. However, students' first attempt at a rule of thumb about making vehicles go farther almost always leaves out that the rule applies to coasting vehicles only. After attaching an axle-driven engine to a coaster car, low friction wheels spin out (accelerating the vehicle requires traction [friction]). Adding friction to the wheel surfaces (e.g., by wrapping rubber bands around the wheels) helps. Clearly, the rule of thumb about low-friction wheels and bearings does not apply to an axle-driven vehicle. To explain why that rule of thumb did not work, students need to realize that friction can be positive or negative and understand the different ways friction can affect performance when combined with other forces. After applying that rule of thumb and discovering that it fails in some situations, they are ready to have this advanced discussion about friction.

By making rules-of-thumb generation and refinement an explicit LBD ritual, we are aiming to provide an easy way for teachers to identify opportunities during design to discuss science concepts. When a rule of thumb does not work, the need to discuss the science is clear. In addition, the discussion motivated by the incorrect rule of thumb may provide the opportunity to go beyond the rule itself. Once students have the need to understand the results of friction combining with other forces, the teacher can seize the opportunity to discuss net force—introducing it if it has not yet been discussed or reinforcing or refining its definition if it was introduced previously.

LBD includes three different kind of *public presentation rituals*—*poster sessions* (see Figure 3), done upon completion of an investigation (experimental or reading a case); *pin-up sessions* (see Figure 2, to present project ideas and justify them); and *gallery walks* (see Figure 2, to present and explain project experiences, several times during the course of addressing the challenge and then at the end).[5]

In a *poster session*, recall, we ask groups to present their investigative setup or procedure, their results, and their interpretations of results, and we encourage peers to ask any questions they need to be able to trust the results and understand their usefulness. Students get experience explaining their methodology in ways that others can understand, and the question period provides a chance to delve deeply into scientific methodology.

In a *pin-up session*, we ask students to present their overall design plan and then to break out the individual design decisions they made and provide justification for each. For example, a group may decide to manage erosion with a combination of planting ground cover and sculpting the land to control water flow. They present a sketch of their full design idea and then discuss the reasons for those two decisions

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[5] The phrase *pin-up session* is taken from the architecture studio, where it is common practice for students to pin their ideas on the wall for others to see and comment on (see, e.g., Shaffer, 1997). In an architecture studio, a student will give a presentation about his or her design ideas while pointing to the illustrations and text pinned to the wall. The term *gallery walk* is meant to bring to mind walking around an art or sculpture gallery—a docent describes an artistic creation to the visitors. In LBD's gallery walks, students present real creations; in LBD's pin-ups, they present ideas.

they made. Students are encouraged to use their own and others' experimental results, science principles or concepts that they know or that have been discussed in class previously, rules of thumb that have been derived so far, their personal experiences, and any expert cases they know about.

A *gallery walk*, on the other hand, is for presenting and explaining the behavior of design creations. As in a walk around an art gallery, one stops to look at and hear an explanation of the artifact being shown off. In a gallery walk, students show off something they have constructed, focusing their presentation on what they were trying to accomplish, what they did to accomplish that, how their device behaves and why, and what they will do next and why. They also ask for any advice they need, and they do often need help with explaining the behavior of their creations and suggestions about what they might try next.

One intention in prescribing all of these presentations is to get students' procedures and conceptions on the table for discussion. If students present experimental results in a way that shows the procedures they used, for example, other students might take the initiative to comment on and question the procedure, providing an opportunity to discuss as a class the practices of managing variables, measuring, running enough trials, and so on. If students present what is happening in a device they have built and ask for help explaining what is going wrong, there is an opportunity for bringing up and doing further investigation on the science concept that will help with that explanation. Another intention is to help the class all move along together at a reasonable pace. Groups that are not making progress can be helped by the ideas gleaned from others during a pin-up session or gallery walk. Another intention is to provide students with a variety of encounters with each practice and concept they are learning. They get to hear about, and often grapple with, the experiences of others in applying concepts and engaging in practices. They get to see multiple examples of the same scientific principle in action, and the teacher has a chance, during the discussion following presentations, to help the students recognize the differences and similarities across what different groups are doing and to extract out important conceptions. Another intention is to prompt students to reflect productively on what they have been doing and interpret their experiences to extract out what they have learned (as CBR says is important to productive learning). Asking them to summarize and articulate to others what they are doing and why requires them to engage in making the kinds of interpretations and connections that CBR says are important. Finally, the public presentations are meant to promote ongoing engagement and motivation. Students in middle school enjoy being the center of attention, and they enjoy it even more when they can provide an idea for someone else to use.

Getting to Understanding

Our intention in LBD is that understanding will happen as a designed-in by-product of interleaving design and investigation. Looking at Figure 1, one can see how these activities promote knowledge building (Scardamalia, Bereiter, & Lamon, 1994). Understanding the challenge includes a set of activities that enact many of the first steps in understanding—exploration, generation of initial ideas and learning issues, and investigation. The other steps in design and redesign provide a venue for trying out what has been learned, noticing inconsistencies, recognizing a need to learn more, and promoting a need to refine and connect together the things one knows.

Scaffolding: Helping Students Productively Engage in LBD and Develop Their Skills

Becoming adept at the scientific, design, communication, and collaboration practices embedded in LBD is not at all simple, and the pragmatics of how to help students gain these skills in the context of learning science content is an important issue for project-based and other inquiry forms of learning. We provide a variety of types of scaffolding within LBD. Design Diary pages, shown in Figures 4 to 6, are used by small groups as they are engaging in small-group rituals. We have tried to design our Design Diary pages (they now total approximately 15 such that they provide organizational guidance without getting in the way, and in such a way that they are useful early in learning and later). We have also designed optional software that provides similar, though more comprehensive, scaffolding (Kolodner & Nagel, 1999). Students can also look in their texts for guidance in using each of the Design Diary pages. We also provide, in the texts, guidelines for engaging in LBD rituals, providing more general guidelines early on and later providing more detail about the specifics to pay attention to in a particular enactment of a ritual. We help our teachers learn to model, coach, and scaffold roles that students will take on, and, as in cognitive apprenticeship, we ask teachers to model student roles early on and gradually turn over agency to the students. Developmental sequencing also plays a large role in LBD's system of scaffolds. The many kinds of presentations and discussions held after them are intended to make students' competence and understanding visible and to provide opportunities to discuss the ins and outs of enacting different skills and practices they are engaging in, and LBD's launcher units (Holbrook & Kolodner, 2000) introduce important skills and practices early in the school year in a context of easier science content.

A SAMPLE UNIT

Vehicles in Motion is an 8-week physical-science unit in which students learn about forces and motion by redesigning vehicles and their propulsion systems. It is our most refined, most successful, and most-studied LBD unit. It has been through four iterations. Its first pilot was in spring 1998, and it has been refined and field tested in each school year since then. Students are challenged to design mechanically powered miniature vehicles that can propel themselves over a hilly terrain and as far as possible.

Getting Started

The vehicle challenge is posed in the context of Antarctic exploration. The children are told that exploration in the Antarctic requires energy-efficient vehicles that can travel over a variety of terrains. They are placed in the role of research team for a consulting organization creating vehicles for Antarctic exploration. Their research team will have write a report to the design team detailing the propulsion characteristics that vehicles will need to navigate the hilly terrain of Antarctica. As members of the research team, they will be designing and constructing models of vehicles that will help them learn best ways of achieving the desired goals. A second, more realistic, design challenge is then posed to them—this one asking them to design and build a miniature vehicle that can travel over a 10-cm and then a 5-cm hill and then proceed as far as possible. We call this their “grand challenge.” In designing their best vehicle and propulsion system, teams must explain the forces at work in their designs and the reasoning behind their design decisions. When this modeling work is complete, students apply what they have learned to the Antarctica situation. In the language of PBL, they are engaged with several problems: learning about forces and motion, making their vehicles work well, and transferring what they have learned to make recommendations about Antarctica exploration.

After reading and discussing the challenges, students get started by “messing about” with toy vehicles (they bring them from home) that achieve or fall short of achieving the grand challenge. A “test track” is set up—the one the vehicles they will be designing and building will have to negotiate—and they try out different toy vehicles on the track. They see which cars can navigate the track easily and which ones cannot. Without any formal understanding, they nonetheless notice the differences between toy designs and their implications. Some wheels provide traction while others spin out on the test track. Some designs provide the torque to get over the hill; some do not. They begin to notice the forces that slow some cars down quickly and bring them to rest while allowing others to coast farther, and they attempt to identify differences in manufacture and construction among the toys that move easily and those that do not. They begin to ask questions: How can I get a car started? Why does this one start more easily than that one? How can I give this car more power to go over the hills? How can I keep it going after it goes over a hill? Is there a way I can increase its speed? How does this one work that is different than that? What mechanisms does it have, and how to they work? And so on. For homework, they try to explain what they saw and to classify the different kinds of propulsion systems they played with.

Messing about is followed by whole-class whiteboarding where students share their discoveries and questions with each other and begin to consider what it would take to achieve the challenge. Discoveries, questions, and ideas are captured on the whiteboard, as in PBL.

Investigation and Minichallenges

That initial set of questions promotes a need to investigate, experiment, read, and explore. It is now, after the students feel that need, that investigative activities are introduced. When we prepare a unit, we anticipate questions students will ask during initial inquiry, and we design investigative modules that address the most important of those questions. Investigation, in LBD, is always for the purpose of achieving a concrete goal. Thus, each investigative module has its own mini design challenge—one that provides physical infrastructure for the full challenge or that helps with generating ideas about how to achieve it. The sequence of investigative modules helps the students focus on the essentials of the science curriculum by guiding them in directions that help them learn the science in the context of achieving the challenge.

During *Vehicles in Motion*, students engage in three minichallenges on their way to achieving the grand challenge. They investigate keeping things going and issues related to friction, gravity, and Newton's First Law[6] as they design and build a low-friction coaster car—one without a propulsion system. The best vehicle is one that can go farthest and straightest after getting started from a ramp. They investigate issues associated with getting things started and combining forces (Newton's Second and Third Laws) during their second minichallenge, in the context of designing and building their best balloon-powered engine. In the third minichallenge, they continue investigating those issues and explore the effects of how a force is delivered as they design and build their best rubber-band-powered or falling-weight-powered car. Each minichallenge lays groundwork for understanding the concepts they need to know to best achieve the full challenge, and each provides students with construction experience and concrete examples of ways they might go about achieving that challenge.

Between minichallenges, they return to the "grand challenge" whiteboard, updating it with what they have learned, new ideas, and new questions, and they regenerate the context for moving into the next module. In the process, the teacher helps students move from questions, "answers," and ideas to (a) specify-

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[6] Newton's First Law states that a body in motion will remain in that same motion until some new force is applied to it; Newton's Second Law explains how forces combine and the effects of changes of mass and force on acceleration (F = ma); Newton's Third Law says that every action has an equal and opposite reaction.

ing what they need to achieve and criteria for judging whether they have achieved the challenge and (b) recognizing the things they need to learn (learning issues) to follow up on proposed ideas, decide which are good, and ultimately achieve the challenge. As part of this discussion, the teacher helps students turn their original design and construction questions into questions about friction, inertia, mass, gravity, speed, and other concepts associated with motion and forces.

For example, classes invariably generate the question, "How can I get a car started?" during initial whiteboarding. During the course of making their coaster cars work well (first minichallenge), they use gravity to get it going and discuss gravity as a force. They might also discuss the notion of net force. Revisiting the whiteboard after addressing the coaster-car minichallenge, the teacher asks the class how to restate that question in terms of changing motion. In one case, the teacher helped students state that starting a car is a change of motion requiring force and helped them transform the question into another one: "How can we give force to a car without using a ramp?" To begin to grasp an answer to that question, the teacher suggested they seek other examples of applying forces to change motion. Eighth-graders usually focus on other vehicles when asked this question—the ones they manipulated during messing about, the ones they played with as children, and real ones. However, if they do not, it is easy for the teacher to prompt for examples. Thinking about the examples, they realize that their vehicles need engines and again restate the question, asking about what kinds of engines they might use to apply enough force to get the car started.

After the three minichallenges are complete, they return to the "grand challenge" and, using everything they have learned, design, build, test, and iteratively redesign their best hybrid vehicle. Figure 7 shows two pin-up posters describing groups' ideas for their final design. They are too small to see detail, but it is clear from them that students come up with very different designs even though they are using the same experimental results. They also do their best to explain how they think their cars will work and why they have designed them the way they have.

At the end, students write up their final vehicle design individually, explaining the design decisions they have made and what they have learned along the way. They work on end-of-chapter-type problems together, applying what they have learned. They also return to the Antarctica Challenge and attempt to transfer what they have learned to addressing it, using what they have learned and experienced about mass, friction, inertia, and combining forces in designing their model cars to justify recommendations to the engineers (e.g., the vehicles need traction to get started in the Antarctica's slippery terrain).

We go into detail on the balloon-car minichallenge to show the interactions between LBD's two macrolevel phases and its microlevel small-group and community rituals in practice.

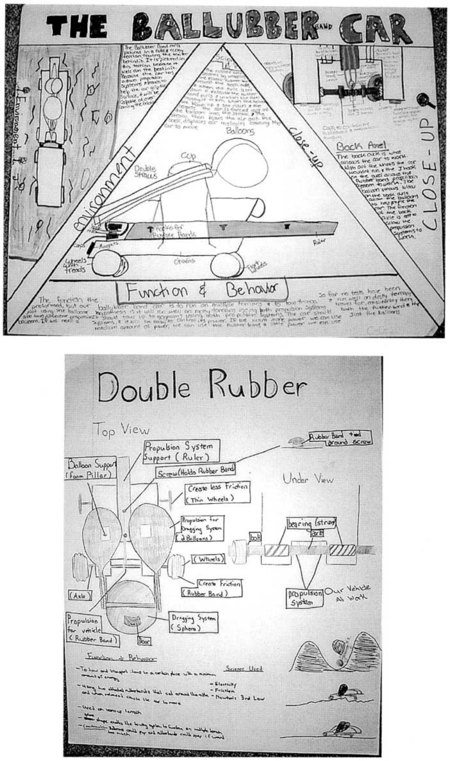


FIGURE 7 Two Pin-Up posters for Hybrid vehicles.

Second Investigative Module: Balloon Cars

The second investigative module in *Vehicles in Motion* answers students' questions about getting things going. It introduces them to propulsion and Newton's Second and Third Laws and reinforces what they have already been introduced to with respect to combining forces, net force, the effect of mass on motion, the effect of force on motion, and so on. We give them baseline instructions for building a balloon-powered propulsion system, and they are challenged to optimize it to allow their vehicle to travel the longest distance on flat terrain. Figure 8 shows several sample balloon cars. One picture shows several students getting ready to test a set of cars against each other, each designed just a bit differently than the others—although all have two balloon engines, some have one wide straw in each balloon, and some use several narrower straws for each. The other shows a balloon car in which students redesigned the body of the car to make it lighter so that it would go further.

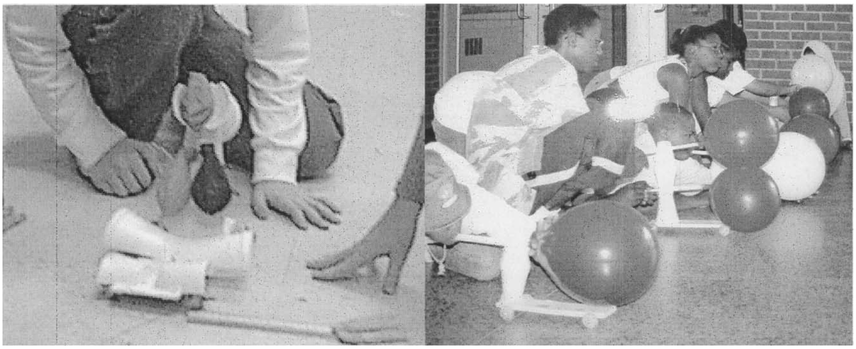


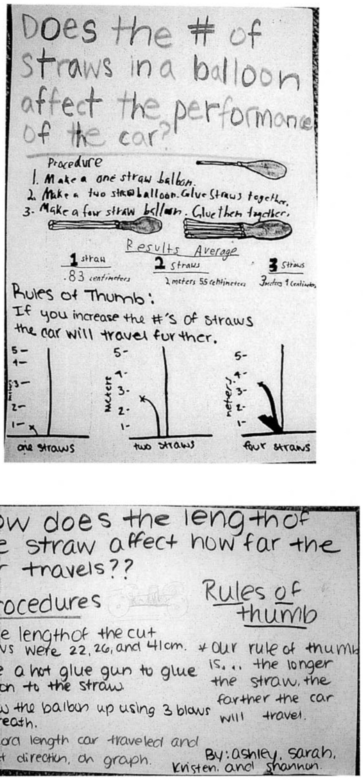
FIGURE 8 Sample Balloon Cars.

Students begin by constructing several balloon propulsion systems and messing about with them—using different size balloons and straws—to see what characteristics, when varied, seem to impact the car's performance (e.g., single- vs. double-walled balloons, multiple balloons, length of exhaust straw, direction of airflow, diameter of exhaust flow). After messing about, the class begins a whiteboard for this minichallenge, focusing on what they need to learn to make the balloon system optimal: Will adding extra balloon engines always make the car go further? Will using a shorter straw always get it going sooner? And so on. Class discussion focuses on turning those questions into learning issues that can be investigated and designing experiments—ideas for answering each question and ways of making sure the answers are valid ones.

In one class, for example, students asked, "How would having the straw pointed down make the car go better?" To help them turn this into a question they could investigate in an experiment, the teacher began by asking them their hypothesis. (He asked that, he says, because he did not understand what they were getting at.) Their hypothesis was that air escaping from the balloon pushes off elements outside the car, so if it pushes off the hard ground and not just the outside air molecules, the students reasoned, then the car should travel further. Now that the students have clarified what they want to test, the teacher helps them turn their question into one that could be investigated, "What effect will a hard surface interacting with the exhaust have on the performance of the car?" Although the teacher knew that there would be no effect, in the true spirit of inquiry, he helped the students design an experiment that could answer this question so that they could find it out for themselves and advise their class members appropriately.

Note, too, that through this interaction, the teacher now knows several of the students' misconceptions: (a) The vehicle relies on exterior objects to propel itself and (b) the angle of the exhaust does not affect travel. Both of those are Third Law misconceptions. We would not expect students to see that yet, but the teacher returns to these misconceptions upon discussions of Third Law later in the unit.

Students divide up the learning issues they generate, and each group designs and runs experiments to answer their question, reporting back to the class when experiments are complete. Figure 9 shows posters from two of those presentations. Class discussion follows, focusing on analysis of the quality of the experiments and how they could have been made better and analysis of how they might apply what they just learned to optimizing a balloon propulsion system. Students might decide they or their peers need to redesign and redo their experiments because they did not manage their variables well enough to pull any useful rules of thumb from them. For example, discussion after presentation of the results shown in the bottom part of Figure 9 included congratulations (from peers) that students had come up with a way of controlling how much air was in the balloon



Does the # of straws in a balloon affect the performance of the car?

Procedure

1. Make a one straw ballon.
2. Make a two straw balloon. Glue straws together.
3. Make a four straw ballon. Glue them together.

Results Average

1 straw	2 straws	3 straws
.83 centimeters	2 meters 55 centimeters	3 meters 4 centimeters

Rules of Thumb:
If you increase the #'s of straws the car will travel further.

How does the length of the straw affect how far the car travels??

Procedures

- the length of the cut straws were 22, 26, and 41 cm.
- use a hot glue gun to glue balloon to the straw.
- blow the balloon up using 3 blows of breath.
- record length car traveled and what direction, on graph.

Rules of thumb

- our rule of thumb is... the longer the straw, the farther the car will travel.

By: ashley, sarah, Kristen, and shannon.

FIGURE 9 Posters from Balloon-Car investigations.

and questions (from peers) about why students chose the straw lengths they did, how they made sure the "blows of breath" were always the same, how far the cars traveled (this one is missing data) and then discussion of how important it is to show data to your peers so that they have the evidence they need to feel they can trust the rule of thumb. Discussion after presentation of the results shown at the top of Figure 9 included questions (from peers) about how many trials they ran for each of their balloon engines and how they made sure that balloon engines always had the same amount of air in them.

Discussion during this segment tends to pull in lessons learned from designing parachutes during the *Apollo 13* launcher unit. In that activity, students invariably run their first experiments without controlling all variables and then have to rerun their experiments more carefully. They learn there about carefully controlling variables and the effects of not running procedures consistently each time. Students tend to remind each other of these needs as they are critiquing each others' experimental results. Rules of thumb that students derive from the results of their experiments also help with this process (e.g., "additional balloon engines provide more force and make the car go farther," "a wider diameter straw gets the vehicle going more quickly"). When students find it hard to believe a rule of thumb provided by another group, they query their peers. It is not uncommon for children to ask each other whether they made sure to blow up the balloon the same each time, how they measured it to be sure, how many trials they ran, why the results from one trial are so different from another, and so forth. Children will ask their peers to rerun an experiment if they see that experimental procedure was violated or if they cannot derive the same rule of thumb from the presented data that some group derived.

When experimentation is done, the class works as a group to refine rules of thumb that have been suggested, and they are added to a public list. The whiteboard is updated, the students now engage in two activities—for homework, as individuals, they work for the next week to write a lab report. As groups, they work together to use what they have learned to begin design of the best balloon system they can construct.

Design begins with planning and then a pin-up session where students present their design ideas to their peers. Students begin their planning as overnight homework, individually coming up with their idea for the most powerful working balloon propulsion system they can build. In class the next day, each group takes its members' plans into account and comes up with their best design, perhaps merging some of the ideas of individual group members. They make a poster presenting their solution idea, both drawing it and describing it. Students are asked to plan what they will construct, to draw sketches of their cars, with force arrows included, for presentation to others, and to include explanations and justifications of each of their design decisions. In their classroom presentation, during the pin-up session, they show off their design plan and justify their decisions based on the experimentation that was completed in the days before. Other students are encouraged to comment, ask questions, and give advice. Students often redraw their plans before embarking on construction, based on discussion during the pinup sessions.

Students continue by building and testing a series of balloon cars, refining their designs until they are satisfied with their vehicle's behavior. The design rules of thumb derived from experiments tell them how each individual variable (e.g., straw diameter, number of balloon engines) affects the balloon cars' performance but not how those variables combine with each other. Constructing and testing different designs allows them to investigate the interactions between variables. They do multiple iterations, using "Testing My Design" pages (see Figure 6) to record the history of their designs and how each performed and sharing what they have accomplished with each other in gallery walks.

Gallery walk presentations provide the opportunity for students to notice problems with the rules of thumb that have been derived and to ask additional science questions. For example, students often experience decreased performance in a balloon car as time goes on because the elasticity of the balloon decreases after multiple uses. This violates their previous understanding of the power of balloon car engines. When the same phenomenon is discovered by several groups, the children are motivated to discuss the pattern. Using guided questioning, peer-to-peer discussion, and actual student products (the vehicles), the teacher can use the gallery walk to help students understand the nuances of the balloon engine. Most important in doing this is to connect science principles to the design experience. The class tries to explain how the design, including its shortcomings, affects the force associated with propelling the car (the decreased elasticity of the balloon means the balloon exerts less force on the air, causing the engine to have less propulsion force).

Gallery walks are also a time for adding clarity to and completeness to rules of thumb. When a rule of thumb fails (e.g., "additional balloon engines provide more force and make the car go farther"), students are motivated to understand why. The teacher can assign readings, provide demos, and so forth. After learning about net force and acceleration, teachers can help students rephrase the rule of thumb above in those terms (e.g., "additional balloon engines that exert force in the direction the vehicle needs to move will create a larger, positive net force in that direction without adding a lot of mass, thus acceleration will be higher and the car should travel a greater distance").

By the end of this module, students have read about, discussed, and experienced the effects of varying mass and force. In addition, they have had experience designing experiments, and they have had significant experience justifying their decisions using evidence (here, from the experiments). A look at their pin ups, and a comparison between those and what they built after several iterations, shows students how far their conceptions have come since they began working on this minichallenge. The pictures in Figure 8 show some students' final balloon-car designs.

At the end of this module, students return to the grand challenge and its whiteboard, updating what they know and what they still need to learn and discussing how they might apply what they have learned. They realize now that you can propel an object if you can generate a large net force on a low-mass object. They have also gained a better understanding of the role friction plays in net force, having had a need to add traction to their wheels if they built very powerful balloon engines. They see that friction is not an outside factor but rather that it should be managed along with the forces that are generated by the propulsion system.

However, typically, balloon power is not sufficient for getting their vehicles over a 10-cm hill. By trying and failing to get their vehicles over the hill, they discover a need for a different kind of propulsion system—one that can exert greater force of propulsion at the start than the balloon-powered system. They move on to the third minichallenge, which addresses this set of issues.

LBD'S ACCOMPLISHMENTS: THE INS AND OUTS OF ADDRESSING CORE CHALLENGES AND REACHING SUCCESS

Earlier, we discussed a variety of challenges to the CBR and PBL framework that we discovered during early implementations, and we introduced the ways we dealt with them as we specialized that framework to create LBD. We revisit the most important of these in this section, focusing on what we have learned is necessary for successful LBD implementation. Our analyses in each area are based on classroom data collected through ethnographic observations over the years of our several pilots and field tests of the *Apollo 13* and *Vehicles in Motion*. However, before that discussion, we present a review of what students in LBD classrooms are learning.

Student Learning

Our design of LBD predicts three aspects of learning that stand to gain from the approach: (a) content knowledge in the target domain, (b) specific science process skills such as those involved in designing experiments, and (c) more general learning practices, such as collaborative skills. Because LBD puts major focus on learning of science and collaboration practices, we expected that LBD students would perform science and collaboration practices significantly better than non-LBD students. We also expected LBD students to learn science content more deeply than their comparisons, but because it is notoriously difficult to show that based on multiple-choice tests, we did not know if we would find evidence for that or not. In our field tests, we have compared knowledge and capabilities of students participating in LBD environments to students in matched comparison classes (with matched teachers). We have taken two major strategies to assessment: (a) assessing content learning by comparing change from pre- to postcurriculum on written, mostly multiple-choice exams, and (b) assessing students' application of science and project practices as they occur during data-gathering and analysis activities and during experimental design activities.

With respect to content learning, our results show that LBD students consistently learn science content as well or better than comparison students (Holbrook et al., 2001). When we analyze the results from individual teachers, we find that the largest gains among our LBD students are often in those classes that are the most socio-economically disadvantaged and who tested lowest on the pretest. Interestingly, these classes tend to have teachers with less background in physical science. We have also seen a trend towards re-engaging girls in science. Scoring on our 1998–1999 data shows that while girls scored lower than boys, as a rule, on pretests, they are equal with boys or ahead of them on posttests.

Analysis of our performance data is more interesting, showing large, consistent differences between all LBD classes and their comparisons (Gray et al., 2001; Holbrook et al., 2001; Kolodner & Gray, 2002; Kolodner et al., 2003). To learn about students' skill competence, we assessed their capabilities when working in groups on a set of performance tasks, before and after the *Vehicles* unit. Our performance tasks, based on tasks from the Performance Assessments Links in Science Website database (SRI International, 1999), each have three parts to them: (a) Students design an experiment or procedure for fair testing, (b) they run an experiment or a procedure that we specify and collect data, and (c) they analyze the data and use it to make recommendations. We video-tape groups of four students working on a performance task and analyze it on seven dimensions: negotiations during collaboration, distribution of the task, attempted use of prior knowledge, adequacy of prior knowledge mentioned, science talk (use of science vocabulary), science practice (appropriate to the task), and self-checks. Scoring is by groups, and each group is scored on a Likert scale ranging from 1 to 5, with 5 being the highest score. Typically, a score of 1 represents no attempt to even participate in the targeted activity, a score of 5 means that almost all students are consistently engaging in the activity over the episode. The coding captures the extent to which students in a group participate in practicing a skill. If more students use the skill, the group gets a higher rating.

Our data show that LBD students consistently perform significantly better than non-LBD students at collaboration skills and metacognitive skills—for example, those involved in checking work—and that they almost always perform significantly better than matched comparisons on science skills (those involved in designing fair tests, justifying with evidence, and explaining). Non-LBD students treat the tasks we give them as simply writing something down. LBD students, on the other hand, negotiate a solution and see the tasks as requiring an experimental design. Most interesting, perhaps, is that when we compare across mixed-achievement LBD students and honors non-LBD students, we often find that mixed-achievement LBD students performed as well or better than non-LBD honors students on skills, meaning that LBD brings normal-achieving students to a level of capability usually found only among gifted or honors students. Table 1 shows data from 1999–2000 and 2000–2001 supporting this analysis.

Challenges of Iteration, Sequencing, and Orchestration

By providing teachers and students with ritualized activities and ways of recognizing what comes next and what each activity contributes to the whole, students and teachers now acclimate quickly. Before introduction of the rituals, teachers typically went through three LBD-style teaching cycles before they began to feel comfortable as facilitators. Since introduction of LBD rituals as approaches to managing and carrying out the macro phases, our teachers are able to do much more effective facilitation their first time through. The rituals give each phase of the LBD cycle some flesh, providing specifics about how to carry them out and clear guidelines for weaving back and forth from phase to phase. Iteration has become a part of the classroom culture that everybody—students and teacher—understand the purpose of and make time for.

Indeed, sequencing and ritualizing activities seems to have helped our teachers understand the active role they need to play in guiding learning from hands-on project activities. When they complete the LBD units, our teachers continue to use whiteboards, hold gallery walks and pin-up sessions, help their students create rules of thumb, and use Design Diary pages as they do more traditional science activities. The students, too, see the usefulness in many of the LBD rituals and ask to continue to carry them on. It is not uncommon, for example, for students to ask for “My Experiment” pages later in the school year. In addition, students particularly enjoy learning from and teaching their peers.

Even with well-defined sequencing in place, however, teachers continue to place more emphasis on early investigative activities than we would like; indeed, the first time they facilitate an LBD sequence of units, they spend far too much time on every one of its parts (our 8-week *Vehicles in Motion* unit sometimes can go on as long as 15 weeks the first time a teacher uses it). When we debrief them after, they tell us that next time they will make the unit shorter by (a) doing a better job of making time constraints clear as students are doing construction and (b) doing fewer iterations, going only until everyone begins to understand the concepts and has something that works minimally, but not aiming for everyone to have a deep understanding and an efficiently working device. It may be that teachers need to do it once in the way they are comfortable with and then reflect on the episode and, with some help, recognize which were the most essential components.

We have learned, as well, that several additional practices, embedded only implicitly in the LBD cycle diagram, seem to be quite important to LBD’s success.

TABLE 1
Results of Performance Assessments for 1999–2000 and 2000–2001: Means and Standard Deviations for Comparison and Learning by Design™ Students After the *Vehicles* Unit

Coding Categories	*1999–2000 Typical Comparison*		*1999–2000 Typical LBD*			*2000–2001 Typical Comparison*		*2000–2001 Typical LBD*			*1999–2000 Honors Comparison*		*1999–2000 Honors LBD*			*2000–2001 Honors LBD*		
	M	*SD*	*M*	*SD*	*t*	*M*	*SD*	*M*	*SD*	*t*	*M*	*SD*	*M*	*SD*	*t*	*M*	*SD*	*t*
Self-checks	1.50	.58	3.00	.82**	$t(6) = 3.00$	1.30	.67	3.88	1.03*	$t(7) = 5.548$	2.33	.58	4.25	.50***	$t(5) = 4.715$	5.00	.00***	$t(3) = 6.197$
Science practice	2.25	.50	2.75	.96		1.40	.89	3.75	1.32*	$t(7) = 3.188$	2.67	.71	4.75	.50***	$t(4) = 4.648$	4.75	.35**	$t(3) = 4.443$
Distributed efforts	2.25	.50	3.25	.50*	$t(6) = 2.828$	1.70	.84	3.00	.00*	$t(7) = 3.064$	3.00	1.00	4.00	1.15		4.25	.35	
Negotiations	1.50	.58	2.50	1.00		1.40	.65	2.88	1.03*	$t(7) = 2.631$	2.67	.58	4.50	.58***	$t(5) = 4.158$	4.00	.00*	$t(3) = 3.098$
Prior knowledge adequate	1.50	.58	2.75	.96		1.60	.89	3.88	.75*	$t(7) = 4.059$	2.67	1.15	3.50	1.00		4.25	.35	
Prior knowledge	1.75	.50	2.25	.50		1.60	.89	3.75	.87*	$t(7) = 3.632$	3.0	.00	3.75	1.50		3.75	.35	
Science terms	1.75	.50	2.75	.96		1.50	.87	2.88	.63*	$t(7) = 2.650$	2.67	.71	3.50	1.00		4.00	.00	

Note. *N* = groups where most groups consisted of 4 students each. Means are based on a likert scale of 1–5, with 5 being the highest rating. Reliability for the coding scheme ranged from 82%–100% agreement when two coders independently rated the tapes. For this set of data, a random sample of four to five tapes were coded for each teacher from one class period. Approximately 60 group sessions are represented in this table, representing 240 students. LBD = Learning by Design. From "Promoting Transfer Through Case-Based Reasoning: Rituals and Practices in Learning by Design Classrooms," by J. Kolodner, J. Gray, and B. Fasse, 2003. *Cognitive Science Quarterly*, *3*. Reprinted with permission.

*$p < .03$. **$p < .02$. ***$p < .01$.

First, our focus in helping teachers and students learn about iteration is not just a focus on iterating towards a good design solution but rather a focus on *iteration toward understanding*. When teachers understand this purpose of iteration, their means of facilitating whole-class discussions is quite different and more like what the science education literature tells us is necessary for transfer (Bransford et al., 1999; Zimmerman, 2000). Teachers who understand this help their students move into investigation when a new question arises that is important to achieving the challenge. For these teachers, presentation times are times for the teacher to help students grapple with what they need to do next and to move activity in directions that will afford the best iterative refinement of student conceptions.

Also embedded in the LBD cycle is a focus *on iteration towards better and more refined scientific practice*. For example, we have found that if students present the results of experiments they have designed and run to others in the class, their peers will question their procedures, providing an opportunity to discuss scientific methodology. If we ask students to redesign and rerun an experiment after such discussion, they have an opportunity to see the differences in the kinds of results one can obtain when running an experiment well versus when it is not run or designed as well.

Another key, we think, that encourages iteration toward more refined scientific practice is *distribution of investigative responsibilities*. When each small group in the class knows some topical area better than others (as a result of investigation), that group becomes the experts at critically analyzing the work of others in the class with respect to that topical area. This encourages engagement; the children like being experts. Also, because every student in the class needs the results of every investigation being carried out to successfully achieve the challenge, everyone in the class is invested in everyone's investigations deriving useful results. Students engage in asking each other questions about their experimental method because they have to know what to believe about what others are reporting to them, and they have to know how to use it.

Also needed for students to iterate towards better scientific practice and understanding, we have found, is a focus on *scientific explanation and justification with evidence*. Pin-up sessions and gallery walks ask for this, and in classes where teachers require students to articulate and justify each of their design decisions and to explain coherently and scientifically to the rest of the class the reasons for the behaviors of the devices they are constructing, more opportunities for engaging in scientific discussion and inquiry arise, and the level of scientific discussion is higher.

Connecting Design Activities to Science Learning

Now that our units provide instructions for building a modestly working device, all children become involved in construction and can be successful. They remain engaged and challenged, and the frustration of not being able to make something work is gone. The sequencing of activities, as well, encourages science talk. Both students and teachers recognize what is expected in different kinds of presentations. Students justify their design decisions by referring back to experimental results during pin-ups. They explain the behaviors of the artifacts they are redesigning using those experimental results and the scientific principles they are learning during gallery walks, and so on. Not surprisingly, the degree to which students connect science to their designs seems to depend on the extent to which teachers model such science talk and the degree to which they require students to rigorously adhere to the requirements of the pin-up sessions and gallery walk rituals. We are in the process of investigating several different ways rules of thumb are being used and the influences of those different ways of using them on students' ability to explain scientifically. Preliminary investigations suggest that students in the classes of those teachers who use them rigorously in the ways we have specified earlier—adding explanations to them as science concepts and principles are learned, using them to raise questions each time someone tries to apply one and fails, and refining their applicability conditions each time someone tries to use a rule of thumb—are able to explain scientifically far better than students in classes where rules of thumb are used simply to guide design (Ryan, 2003).

Creating a Classroom Culture and Ethos

In classes where our teachers have helped students learn from the beginning that they are all responsible for each others' learning, where the teacher makes clear that he or she respects the students as learning partners, where the teacher engages with the students in addressing the design challenge, and where the teacher insists on respect towards everyone, the students respond quickly, engage enthusiastically, and learn much, even when teacher skills and knowledge are deficient. When the teacher goes through the motions on all of the activities but makes no changes in the classroom climate, the students do not engage well either. In classrooms where the teacher models scientific reasoning and enforces it from the students, the students learn those skills, and their science content learning is better.

The most important value we teach our teachers may be collaborative learning. We try to help our teachers understand that collaborative learning is not simply a call to have students work in groups, but rather, it is a value that needs to permeate the classroom—through sharing across groups, more expert students helping less expert ones, the teacher admitting what he or she does not know and getting excited about learning from the students, the students together figuring out what they need to learn more about and helping each other with their investigations and experiment designs, and so on. We ask them to take the idea of communities of learners (e.g., Brown & Campione, 1994; Campione, Shapiro, & Brown, 1995) very seriously.

This value, as an umbrella, combined with the rituals and cycles, allows many other values to be enacted in the classroom, for example, students as experts, the noncompetitive nature of groups (friendly competition only), performance that shows understanding, scientific method and science as a process, decision making based on evidence, doing and experiencing to gain understanding, setting and meeting expectations, and science as a way of understanding and affecting the world.

Even though LBD challenges are unlike what students are used to, when teachers enact these values in the context of LBD activities, LBD becomes a way of life quickly for them. By one month into the school year, students in some classes have begun to develop the full range of practices and values that LBD entails in addition to being enthused and engaged by the activities. They are able to talk about such things as designing experiments, needing to manage variables, and measuring well. They take an active role in helping their classmates move forward, and they enjoy being the expert at times when they have expertise that others do not. In all of the LBD classes we have observed where the teachers are enthusiastic, by the end of *Vehicles in Motion*, nearly every student has learned to take part in LBD's rituals, virtually every student has successfully addressed the challenges, and nearly every student is engaged and enculturated to the point where the last thing they want is to go back to the old ways. Even in our urban classes where the children struggle to fulfill their responsibilities as group and class members, they can talk about what they ought to be doing, point out the difficulties in what they are doing, and eventually take on appropriate responsibilities. In addition, teachers report to us that the discipline problems in their classes are greatly reduced when they are engaging in LBD activities.

One explanation is that the rituals of LBD offer a hook that engages students who do not consider themselves to be math or science scholars. For example, a group of girls who described themselves as being "more of a language arts student[s]" reported being more successful in science through LBD because it gave them the opportunity to apply and be appreciated for what they perceived to be their strong suits (i.e., writing skills, using what they know from everyday experiences, verbal skills, and group process). Because their skills were being utilized, and because they were having success with assignments, they were more invested than they claim ever to have been in previous science classes. For these "nonscience" students, there seems to be magic in discovering that science is not merely a class one suffers in school, but that the science curriculum is a representation or explanation of their everyday world and experiences. This is a powerful revelation for many kids.

Teacher Challenges

On the other hand, teacher challenges and system challenges remain. Not all of the teachers who have field tested LBD for us are master teachers, most have not known science well, and most have not had much experience, if any, taking an inquiry or project-based approach in their teaching. Most, on the other hand, have been enthusiastic about wanting to help their students learn more and have therefore applied themselves intently in learning how to be an LBD leader. We have helped them learn LBD through an intense 3-week summer workshop that allowed them to experience LBD as their students would, reflect on their activities to learn about LBD and to learn science content and skills, and that included time to try out their new facilitation skills with summer-camp participants. There are some things teachers find more easy than others, but eventually they catch on. Their biggest difficulty has been control. We have tried to help them understand that they do not have to give up control in an LBD classroom, but rather that they need to control very differently. For some teachers, this transition has been too hard and they have pulled out of our field tests or quit after a year. Our observations suggest that willingness to change the way one controls a class is a key to success. Teachers cannot always facilitate LBD well right away, and many have trouble learning the science, but if they have bought in to *what could be* in the classroom and if they have help as they are learning to implement the new approach, their classes thrive, and students and teachers learn together (even if teacher content knowledge and skills start off weak). Providing teachers the time needed to learn new skills and then the supportive environment in which to hone those skills during the school year will be major challenges in broadly disseminating any LBD-like approach.

CLOSING THOUGHTS

Our intention, when we began development of LBD, was to create an approach to science education that could be broadly used nationally and world-wide—one that would address the cognitive and social needs of middle-school students, that would address key content areas as designated by science standards, that would be adaptable to a variety of classroom circumstances, and that would help teachers learn to be better teachers at the same time it helped students to learn science and the practices of scientists, engineers, and team members. To make that happen, we knew we would have to write and publish a set of units, each with student texts and teacher handbooks.

This was and remains an ambitious goal and one that is relatively novel within the learning sciences community, as the energy that needs to go into writing materials in ways that make them broadly usable is enormous. Our experience of moving from theory to practice suggests several hypotheses about the design of learner-centered, inquiry-oriented, and project-based curriculum approaches.

First, creating a classroom culture that values collaboration and iteration seems critical for enthusiastic engagement and the kinds of reflection, abstraction, and discussion that are critical for deep and transferable learning. Creating that culture is a long-term event and needs to be planned for in the curriculum approach, taking into account teacher culture and knowledge as well as student culture and development. One cannot assume that the culture will arise by itself, and one cannot assume that it will sustain itself without constant reenactment. The lessons of Fostering Communities of Learners (Campione et al., 1995) need to be taken seriously. Beginning with launcher units as we did may be a key. Certainly the repetition of core activity sequences that embody those values is important.

Second, learning skills and practices is a developmental process—whether the practices involved in doing science, working together as a team, working together as a class, planning a project, or others. One cannot assume that students (or teachers) will be able to execute practices in proficient ways from the beginning. Modeling by the teacher, consistent practice by students, and reflection on, articulation, and imagining what would work better are all needed. Our experience shows that middle-school students are capable of far more than they are generally given credit for. Scaffolding the learning of science, design, and collaboration practices brought LBD students to a level of metacognitive awareness and capability in performing those practices that far outpaces what students in more traditional classes were able to do. We need more research on what middle-school students are capable of with scaffolding, and we need to design more classroom materials that will help teachers help students learn important skills deeply.

Third, there seem to be four critical times for students in a project-based science classroom to share their ideas and results with each other—after investigation, after planning a project solution, during the implementation process, and at the end. Reporting on investigations promotes thinking about the scientific methods they are using, reporting on what they plan for their solution asks them to connect evidence to decisions, reporting during implementation gives them practice using science to explain, and a final report is a good time to draw everything together and reflect on collaboration and community practices along with science content and practices. However, it is shortsighted to think of a report as an end product; rather, presentations used at interim points in the learning cycle give students a chance to gain a broader perspective than they can take in their own small groups. Providing time after presentations for rethinking and revising and perhaps rerunning investigations and reporting once again enacts a truly collaborative and iterative culture.

Fourth, the curriculum approach by itself cannot do it all. Engagement by middle schoolers seems to require engagement by the teacher, respect from the teacher, and setting of expectations by the teacher. Teachers who set expectations and hold students to them while trusting students and helping them achieve expectations seem to be the most successful in helping their students learn. When teachers think about learning as iterative refinement coupled with a culture of collaboration and help to make that happen in their classrooms, students engage enthusiastically with learning.

Fifth and finally, no one educational, cognitive, or sociocognitive approach has all the answers. An approach that comes purely from research will not be complete, as research is still incomplete. We began with CBR and PBL as a base. CBR told us much about how to promote transfer. PBL about how to orchestrate learning. However, we needed to pepper the approach with contributions from fostering communities of learners, constructionism, architecture studios, and cognitive apprenticeship, among others, to make it complete. We found, as well, that even taking a full range of research literature into account, we still needed to consult the wisdom of teachers and to discover more about the classroom than had been documented to get to a set of practices that could be enacted consistently. Even that was only enough to get us to proof of concept. Getting to broad dissemination requires even more, for example, dealing with systemic issues inherent in school systems. Nonetheless, we want to challenge the learning sciences community to engage in more endeavors of this kind—taking approaches from conception to proof of concept and, when possible, all the way through to broad dissemination in real classrooms.

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