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Designing to Learn About Complex Systems

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Complex systems are commonly found in natural and physical science. Understanding such systems is often difficult because they may be viewed from multiple perspectives and their analysis may conflict with or extend beyond the range of everyday experience. There are many complex structural, behavioral, and functional relations to understand as well. Design activities, which allow explorations of how systems work, can be an excellent way to help children acquire a deeper, more systemic understanding of such complex domains. We report on a design experiment in which 6th grade children learned about the human respiratory system by designing artificial lungs and building partial working models. Structure–behavior–function models are used as a framework for the cognitive analysis of the domain. The design activities helped students learn about the respiratory system. The design students indeed learned more than students receiving direct instruction. They learned to view the respiratory system more systemically. As expected, because of the short time they spent on the exercise, they understood more about structure than function and more about the functions of

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different parts of the respiratory system than its causal behaviors. This early Learning by Design experiment makes several important suggestions about successful learning from design activities: (a) the need to define design challenges functionally; (b) the importance of dynamic feedback; (c) the need for multiple iterations toward a solution; and most important; (d) thinking about design as a system of activities and allocating time so that the full system can be carried out, allowing its full set of affordances to be realized.

A car engine. An air conditioner. Weather patterns. A biome. Human respiration. All are complex systems. We need to learn about complex systems to satisfy common human needs and curiosities and to solve real world problems: "When is it going to rain?" "How could someone breathe without healthy lungs?" But complex systems have many characteristics that make them difficult to understand. Understanding a system involves considering the causal interactions and functional relations between parts of the system and with other systems. But some interactions between parts are invisible, and some have a time sequence that makes them difficult to perceive. Indeed, it is notoriously difficult even for adults to learn about complex systems (Feltovich, Coulsen, Spiro, & Adami, 1992). Yet understanding how complex systems work is often critical to scientific analysis.

Penner, Giles, Lehrer, and Schauble (1997) demonstrated that constructing a deep understanding of a natural mechanical system (the elbow) is possible, even in elementary school students, through a process of modeling—iteratively constructing and testing better and better models of the system being learned. We build on that work, taking it into the middle school, with the aim of helping middle school students learn a more complex system (the respiratory system) through a combination of modeling and design. In an attempt to design an artificial complex system (an artificial lung), students designed and constructed models of a naturally occurring complex system (a part of the respiratory system).

We build, as well, on Perkins' (1986) "knowledge as design" approach. The traditional approach to teaching about complex systems has been to present the structural elements of a system as a series of related definitions. Students memorize the definitions, they might draw posters of the system, and answer questions at the back of a chapter. But such an approach often does not lead to the understanding of what they are learning as a system (i.e., as a united whole with parts whose functions interact with and influence each other). To alleviate that, Perkins suggested helping students view systems as designs: structures adapted to specific purposes. Viewing a system as a design goes beyond simply defining the parts, and also addresses their functional roles, the mechanisms by which those roles are carried out, and how those functions causally interact with each other.

Such an approach has the advantage of more completely considering a system as a union of functionally related subparts, but it does not address how students can be motivated to be engaged in such learning, nor does it address how we can sup-

port students' evolving understandings from superficial to deep. The Learning by Design (LBD) approach (Kolodner, Crismond, Gray, Holbrook, & Puntambekar, 1998) takes those next steps—we ask students to not only think of systems as designs, but, in addition, to understand some natural design (e.g., the lungs) well enough so that they can undertake the design of an artificial system that can carry out the same functions. Students need to be actively engaged in design and modeling activities to learn about complex systems. Our hope was that, through such engagement, students would learn connections between the structures and functions of the respiratory system and the causal behaviors that allow them to work.

Our goals in this study were threefold:

1. We explored the extent to which a design approach could be used to help children learn about a complex system, the human respiratory system.
2. We examined the potential advantage of designs' implicit emphasis on structure–behavior–function (SBF) relations to help children think more deeply about complex phenomena.
3. We investigated ways of implementing a design approach in a middle school classroom. Design has many affordances for promoting deep learning of systems, but there are many unanswered questions: What kinds of design challenges are most appropriate? How can we help students remain focused? How can we ensure the science content is covered? How should to design activity be organized to promote deep understanding?

We report on a design experiment (Brown, 1992) in which children learned about the respiratory system by designing and building a model of one component of an artificial lung. Our results indicate that design students indeed learned more about the complexities of the respiratory system than did students in a traditional classroom; it shows as well where they failed to learn as deeply as we wanted. They learned to think more systemically, but not all of their understandings were correct, particularly at the level of causal behaviors. This combination of results suggests that a design approach indeed has potential in helping students learn about complex systems. It also leads to suggestions about how to more effectively use design as a vehicle for learning about systems. This early experiment in learning about systems through design activities has allowed us to add significant sophistication to the approach to science learning we have been developing called LBD (Kolodner et al., 1998).

LEARNING ABOUT COMPLEX SYSTEMS THROUGH DESIGN ACTIVITIES

Many natural and manmade systems are quite complex and depend on local interactions as well as executive control processes. Moreover, complex systems may be

understood at multiple levels of organization (Ferrari & Chi, 1998; Groothuis, Boshuizen, & Talmon, 1998; Wilensky & Resnick, 1999). For example, in learning about ecological systems and evolution, one needs to envision how genes, individuals, populations, and species interrelate. In human biology, phenomena occur at the anatomical, biochemical, and physiological levels. In addition, there are properties of human systems that operate at both macroscopic and microscopic levels. It is impossible to understand these systems at different levels without understanding the emergent functioning of the entire system (Resnick, 1996). These systems often depend on local interactions of components of the systems, and the function of the entire system may appear quite different from the behavior of individual elements. For example, Resnick (1996) provided the example of a traffic jam in which the individual cars are moving forward (albeit slowly), whereas the jam itself is moving backwards.

Systems are dynamic entities, and many of their organizational levels are difficult to visualize, such as cellular respiration. Part of the difficulty individuals have in understanding complex systems can be related to the way students are introduced to them (Feltovich, Spiro, & Coulsen, 1993). Often, learners are introduced to complex systems in oversimplified static forms, and these early conceptions form schemas that are then difficult to overcome. In life science, in particular, there is often an emphasis on understanding isolated concepts without introducing learners to the interrelations among various levels of the systems.

An approach to systems from artificial intelligence, called SBF theory (Goel & Chandrasekaran, 1989), provides some vocabulary for thinking about how to describe systems. In attempting to have the computer design and debug systems, Chandrasekaran and Goel discovered that a representation that highlights structures, functions, and behaviors of systems, and the connections between those parts, allows for effective reasoning. Structure refers to the physical structures of a system; for example, the lungs are a physical structure in the respiratory system and the alveoli are physical structures within the lungs. Function refers to the purpose of the system or subsystem. The respiratory system transports oxygen throughout the body to the organs that require it; the lungs extract oxygen from air. Behavior refers to the dynamic mechanisms and workings that allow the structures to carry out their function; that is, the mechanisms that cause changes in the structural state of a system. The most accessible behaviors are the visible ones (e.g., air going in and out of the nose, the chest moving). But behavior is far more than what one can see (e.g., the invisible electrical impulses traveling through nerves that cause the respiratory system's involuntary movements). We can describe behaviors using a language of causality—some action causes some state enabling some other action. Understanding "invisible" and time-delayed causality is a big part of what makes behavior so difficult to understand. Because invisible and time-delayed causality are so difficult to understand (Feltovich et al., 1992), behavior is the hardest aspect of systems to understand. Novices tend not to consider that a

system has behavior until some anomaly in the normal function of a system arises and they have a need to debug or explain it (Murayama, 1994). Table 1 presents a simplified analysis of the respiratory system in SBF terms.

One of the major challenges for helping students learn about systems is keeping them focused on their deeper functional and behavioral levels rather than just on their structure. Because structure is visible, novices typically begin to understand a system at a superficial structural level, only later beginning to understand how structures are related to each other through behavior and function. On the other hand, when experts reason about systems (e.g., for design or diagnosis), they typically reason first at the functional and behavioral levels (Chi, Feltovich, & Glaser, 1981). It was our hope that, through design challenges and modeling activities that focus on behavior and function, we would be able to promote focus on behavior and function and help students move from novice to more expert understanding of the respiratory system and of "systems" in general. We asked middle school students to learn about a complex human biological system (the respiratory system) by coming to an understanding of its structure (e.g., anatomy) and function (e.g., physiology) in the context of each other and by building a model of some piece of it that would integrate structure and function through behavior.

Designing Affords Such Understanding

Design activities are particularly well-suited for helping learners understand systems because of their emphasis on functional specification and their requirement that behavior be implemented. Design problems require a designer to identify ways of accomplishing desired functions and fit them together to create a system or artifact. Often, there are several ways of accomplishing each function, and the designer needs to consider each and decide among them, requiring an understanding of nuances in func-

TABLE 1
Simplified Structure-Behavior-Function Model of Respiratory System

Structure	*Behavior*	*Function*
Lungs	Gas passes from high concentration to low across semipermeable membrane.	Bring in oxygen *for cells*, remove waste *from cells.*
Diaphragm	Lower pressure in chest by increasing volume.	Move *lungs* so they can take in fresh air.
Brain	Send signals *to respiratory system*. Receive and process *signals regarding body status.*	Control or regulate *movement of lungs in response to changing metabolic needs.*

Note. Italics indicate connections with other systems.

tions, behaviors, and the principles behind accomplishing them. Designers also sequence and interrelate multiple functions. They continually evaluate how completely functional requirements are satisfied. Because of their emphasis on function and iterative refinement, achieving design challenges has the potential to afford exploration of issues important to understanding science concepts. In addition, as students solve design problems, they come to understand how knowledge is structured and interwoven with purpose, function, and causal relations (Perkins, 1986).

Design places students squarely in the process of constructing rather than receiving knowledge (Lehrer, 1993; Perkins, 1986). The process of design initiates students into the discourse that typifies communities of practice in science and engineering (Roth, 1995). By participating in such practices, students learn to use concepts and heuristics as tools for problem solving. Discussion about the designed artifacts facilitates sharing of knowledge—the artifacts they are designing can serve as concrete referents that students focus attention on as they are communicating (Roth, 1996). The process of designing, as well as the product, can play important roles in promoting learning (Kafai, 1996).

Design professionals use modeling as a vehicle for understanding the problem they are working on and making predictions about how their design might behave when constructed. In the classroom, the process of designing affords the potential for learners to construct, apply, and evaluate models (Kolodner et al., 1998; Penner, Lehrer, & Schauble, 1998; Roth, 1996). Students may construct a model of the device they are designing, of some part of it, or of some mechanism they need to learn more about to achieve their design goal. The design, construction, testing, and refinement of models provides a powerful means of coming to know our world and thus offers the potential to enhance understanding in scientific domains (Penner et al., 1998). As students design models, they need to describe, predict, or explain some phenomena, which requires them to discuss and invent objects and their relations to each other as well as to consider functions and causal behaviors of the components in their model.

Such learning can happen only if students are working with models of appropriate fidelity and complexity. Appearance-based models do little to enhance one's understanding of how things work. Through appropriate iteration, including exploration of the advantages and disadvantages of initial models, though, even young children can move from design of appearance-based to design of functional models fairly quickly. For example, during their first elbow modeling activity, Penner et al. (1997) found that children's predilection to focus on perceptual similarity competed with the need to focus on function. But when these students had the opportunity to revise their models of elbows after exploring and articulating real world constraints on elbows, they were able to incorporate appropriate functional constraints into their appearance-based models.

Linn's work (Linn, 1995: Linn & Muilenberg, 1996) also suggests the need for multiple iterations during modeling, to help students make connections between

concrete situations and the models they are constructing and testing, and to help them construct progressively more sophisticated understandings of the system they are learning about. That work suggests several types of scaffolding that are needed to promote making those connections—help with identifying new goals for learning, making one's thinking visible, and seeking answers to questions one has generated—with the ultimate goal of helping students anticipate and seek out better and better models to explain phenomena. Linn (1995) pointed out that it is possible that there can be progression in which some aspects of children's understanding of a system are complete, while other parts are still quite naive. For example, we might expect to see relatively sophisticated understanding of function and functional relations among structures while still seeing a failure to consider causal behavior in depth. Thus, students will have differential understanding of the respiratory system and its parts—some will understand more than others; each might understand different aspects of the respiratory system, and a 2-week experience with the respiratory system can only begin to help students understand it systematically.

Modeling and design have many similarities—both lead to the construction of an artifact, and both require managing the interconnections between a variety of structural and functional parts. When the goal is to create a model, success is judged in terms of whether the model elucidates the phenomena being studied. When design is the goal, criteria for success are the satisfaction of functional constraints. We borrow from both traditions, asking students to use design practices to come to an understanding of the issues involved in achieving a large and complex design challenge (designing an artificial lung), to focus investigations on some of those issues (e.g., How do human lungs work? What artificial mechanisms can model the functions of human lungs? How do lungs connect to other organs?), and to construct and test models to answer those questions.

Although the design challenge posed for students was too large and complex for them to actually succeed in achieving it (indeed, experts have not yet been able to achieve this goal), we expected that their interest in investigating how artificial lungs might work would motivate them to want to learn about the respiratory system and to build models of some of the functions of real and/or artificial lungs. Although we did not expect students to complete the design, we did expect that they could come up with simple ideas about how to proceed on some piece of such an artifact, or that they could identify a set of issues that would have to be addressed. Achievement of either of those goals requires a deeper un erstanding of the respiratory system than is typically promoted in middle school biology.

IMPLEMENTING LBD

Implementing learning from design activities is a complex undertaking that needs to be carefully orchestrated (Barron et al., 1998; Kafai, 1996; Kolodner et al., 1998; Lehrer, 1993; Penner et al., 1998). The process of design requires students to man-

age multiple constraints while dealing with complex situations (Kafai, 1996). Schauble, Klopfer, and Raghavan (1991) reported that, when children conduct experiments, they often focus on creating outcomes rather than constructing understanding. This is understandable because the outcome (some artifact that works) is a concrete product, whereas understanding the internal workings of a system is more abstract and less tangible. There are many difficult tradeoffs in using design to promote learning in the classroom (Barron et al., 1998; Schauble et al., 1991):

1. Finding a balance between having students work on design activities and reflecting. Incorporating reflective activities is important to encourage an understanding-oriented approach.
2. Learning how to integrate real world knowledge without letting it overwhelm the class with irrelevant aspects of the world that might take the students on unproductive tangents.
3. Determining how to maintain extended student engagement in a manner that emphasizes principled understanding rather than task completion.

A key issue for us was to develop a system for managing the activities of the classroom that would take these many issues into account and that would keep students focused simultaneously on the science they were learning and its purpose and use for a real world purpose. We had to worry, as well, about helping students to manage their knowledge construction and integration (Linn & Muilenberg, 1996).

Our initial approach (Kolodner, Hmelo, & Narayan, 1996) was predicated on problem-based learning (PBL; Barrows, 1988; Hmelo & Ferrari, 1997), an implementation of cognitive apprenticeship (Collins, Brown, & Newman, 1989) that focuses on learning through complex problem-solving activity. We refined the PBL model based on lessons learned by those working on modeling approaches (Linn, 1995; Schauble et al., 1991) and learning about complex systems (Feltovich et al., 1992), and others working on learning from design activities (Kafai, 1996; Lehrer, 1993) as well as findings from case-based reasoning (CBR; Kolodner, 1993) about learning from problem-solving experience (Kolodner, 1997). Based on the advice of collaborating teachers, we developed design challenges that afforded sustained thinking about topics in the middle school science curriculum and that would be interesting for middle school students. Designing an artificial lung was one of the challenges that we developed along with our teachers.

PBL provided the base for integrating doing with reflection and for helping students make connections to the world around them (Barrows & Kelson, 1995; Hmelo & Ferrari, 1997; Savery & Duffy, 1995). A PBL session begins by presenting a group of students with a complex problem to solve. While working on understanding the problem, students pause to reflect on the data they have collected so far (FACTS), generate questions about those data, and hypothesize about underlying causal mechanisms that might help explain those facts or potential solutions to

the problem they are working on (IDEAS). They identify concepts they need to learn more about to solve the problem (LEARNING ISSUES) and then they develop a plan for proceeding (ACTION PLAN). The first part of that plan is generally investigation—students divide up and independently research the learning issues they have identified. They regroup to share what they have learned, reconsider their ideas, and/or generate new ones in light of their investigations. They continue by attempting to solve the problem based on what they have learned, sometimes cycling several times through question generation and additional research. The dynamically changing lists of facts, ideas, learning issues, and action plan are recorded in columns of a public whiteboard, as shown in Figure 1. The whiteboard is revisited and updated on a regular basis. The whiteboard helps learners remember where they have been and where they are going in their learning and design. It helps focus negotiation of the problem and provides an anchor for students to co-construct knowledge. After completing their task, learners deliberately reflect on their experience to abstract the lessons learned and to consider how they performed in their self-directed learning and collaborative problem solving.

Facts	Ideas	Learning Issues	Action Plan
Diaphragm is primary muscle for resp	Will the artificial lung be like the real lung	How does CO2 get out of the body	Collect materials that are elastic, spongy, light, absorbent
Diaphragm goes up causes difference in pressure in lungs	Will we need to build different sizes for different ages?	How much O2 does body need?	Dissect a mammal
Adult lung holds 3 liters air	Need to make sure the body gets all the air it needs.	How will we measure that the body gets enough air?	

FIGURE 1 An example whiteboard.

The facilitator (i.e., teacher) is responsible both for moving the students through the various stages of problem solving and for monitoring the group process—ensuring that all students are involved and encouraging them both to externalize their own thinking and to comment on each other's thinking (Hmelo & Ferrari, 1997; Koschmann, Myers, Feltovich, & Barrows, 1994). The facilitator plays an important role in modeling the needed thinking skills. Another important role the facilitator plays is helping students bring in their knowledge of the world as a contribution to problem solving while at the same time helping them to move forward without being overwhelmed by the magnitude of the problem. That can be carried out by allowing any and all ideas and questions to go onto the whiteboard initially and then guiding discussion toward identifying the more realistic and important ones, helping students create an action plan that has them investigating only the most important of the questions raised. Although the facilitator fades some of his or her scaffolding as the group gains experience with the PBL method, he or she continues to actively monitor the group, making moment-to-moment decisions about how best to facilitate.

PBL is less informative about how to manage construction and testing activities and keep students focused on the design challenge. To accomplish this, we added practices suggested by CBR (Kolodner, 1993, 1997; Schank, 1982, 1999). CBR was developed as a way of allowing computer programs to solve complex problems. Its development was based on observations of experts—particularly their ability to learn from experience and re-use knowledge learned in one instance in another instance. CBR, as a method for computer reasoning, focuses on storing problem-solving experiences (cases) in a case library, interpreting and indexing them so that they could be found and re-used at appropriate times, ways of searching that case library to find appropriate cases, and adapting and merging the solutions to old cases to solve new problems. Modeling these processes on the computer provides suggestions about how we might promote such learning in people. CBR's suggestions are in keeping with much of what is proposed by constructivist education and in keeping with the classroom experiences of researchers looking at learning in the classroom (e.g., Feltovich et al., 1992; Linn, 1995; Penner et al., 1998).

CBR shows that learning is an iterative process: One's initial conceptions are often incomplete or faulty, and only by trying them out, seeing if results are as one expected, and attempting to explain ensuing anomalies can one discover the holes in one's knowledge and be motivated to fill them. Thus, according to CBR, deep understanding requires the experience of one's expectations failing and the subsequent need to explain why. One's expectations fail when one tries something expecting one result and a different result ensues. When one fails at something one wants to accomplish or understand, one is motivated to explain the failure (i.e., to learn more). Conversely, it is difficult to recognize a lack of understanding without the opportunity to try out ideas and observe what happens. In our teacher training,

we emphasized to the teachers that students needed to actually build and test something based on their understanding, get concrete feedback from that testing (i.e., by evaluating how well it worked), explain what happened, revise their understanding, and try again. This focus on failure and explanation is consistent with Linn's (1995) and Schauble et al.'s (1991) work on learning about models, but adds to their work the need to actually construct and try something out and see how it works. The combination of these insights led us to add multiple cycles of designing, constructing, testing, explaining, and revising to the PBL framework.

CBR also provides pointers about which kinds of interpretations of one's experiences will result in being able to transfer what one has learned in one situation to another situation. CBR suggests that the better the connections between one's goals, one's solutions, and their outcomes, and the better one has articulated those connections in explanations, the better one will be able to re-use the results of one's experiences. We therefore suggested to teachers that they have students present their ideas and partial solutions to each other, along with what they observed and their explanations, and that teachers help students to explain their results. PBL already had in it the mechanisms for making one's thinking visible—students are asked, in PBL, when they have a new idea, to explain where it comes from, and at the end of a problem, they discuss the processes they used to come to a solution. We added to that a focus on outcome and explanations of those outcomes.

As well, CBR suggests that good indexing of one's experiences results from extracting lessons one can learn from one's experiences and anticipating when those lessons might be applied in the future. We therefore suggested that reflective sessions at the end of a challenge include extraction of lessons learned and anticipation of their use.

To this mix, we refined PBL's traditional implementation to make it amenable to a middle school classroom. Students would work in small groups of three or four on investigation, construction, testing, interpretation, and redesign activities; most reflective activities (planning, monitoring, and mindful abstraction) would be done as a whole class facilitated by the teacher; and the class would be brought together for such reflection on a regular basis. It was important that none of the small groups forget the purpose of their activities or be left behind. Whiteboarding was thus to be done as a whole-class activity, with several cycles of small-group and whole-class activity during the course of a class period. Design, testing, explanation, and redesign would be the central cycle of activity and provide purpose to student inquiry. After each investigative activity and iteration of the design process, students would return to the whiteboards and update them with what they learned from their design and testing, see which learning issues need to be addressed and which ones still need to be added, and discuss how to modify their initial action plans. The whiteboard would be the device for recording shared experiences, insights, ideas, and questions, and for focusing discussion and reflection. This was our original conception of LBD.

THE DESIGN EXPERIMENT

Our goals, as stated earlier, were to (a) learn the extent to which a design approach could be used to help children learn about complex systems, (b) learn to what extent an emphasis on SBF relations would help children think more deeply about complex phenomena, and (c) understand how to promote learning from design activities. To this end, we worked along with our collaborating middle school teacher, Mr. D, to develop the lung problem and set of classroom activities that would support it, trying our best to work within the framework described earlier while also working within the constraints of a middle school classroom. The study described here, carried out in Spring 1996, was one of our earliest attempts at implementing LBD in a classroom. Thus, we not only began to learn the answers to the questions we had posed, but we also learned many of the pitfalls of implementing a design approach in a middle school classroom. In the rest of this article, we present a case study of Mr. D's two classrooms, our analysis of the implementation, what the students learned, and the lessons learned by our research team.

Participants

There were 42 students in the two experimental (LBD) classes. A subset of students ($n = 20$) was randomly selected for pre- and postinstruction interviews. Students from a comparison classroom at the same school participated in the study as well. Students in the comparison classroom spent 2 weeks learning about the respiratory system; they learned by reading their textbooks and participating in lectures and teacher-directed classroom discussions. Comparison students engaged in the same pre- and posttests and some of the pre- and postinterviews that students in the LBD classes engaged in. The data from these students help us ascertain which of our learning outcomes were due to the LBD approach.

Mr. D, the teacher, had participated with us in a summer workshop to learn about using design challenges for promoting science learning and to how to facilitate PBL classrooms. He had experimented with PBL earlier in the year, but this was his first prolonged experience doing PBL or LBD.

LBD Classroom Setting

The setting for this study was two 6th-grade life science classes taught by Mr. D in suburban Atlanta. His students were a heterogeneous group—mixed gender, ability, and socioeconomic status. During the 2.5 weeks of this project (13 class periods), Mr. D arranged to use a large science lab with ample workspace. The two classes worked separately. They had eight Macintosh computers available during

the time they worked on the project, spaced around the periphery of the room. The computers made supplementary resources available. Each computer also held an online whiteboarding program, called McBagel (Hmelo, Narayanan, Hübscher, Newstetter, & Kolodner, 1996). There was a large-screen monitor at the front of the room to project from one of the computers.

Data Collection and Analysis

We collected two kinds of data. First, we collected data that could tell us what students were learning and about their understanding of the respiratory system. Interview and written data were collected to examine the students' pre- and postinstruction understandings of the respiratory system. Prior to instruction, 20 target students were interviewed regarding their knowledge of the respiratory system and asked to draw diagrams of the respiratory system. Students were asked open-ended questions about breathing and then asked about each component of the respiratory system, in a manner similar to Chi, de Leeuw, Chiu, and LaVancher (1994; see Appendix for questions). Inference questions were posed to see how well students could use their knowledge. All the students in the LBD and comparison classes were given a 12-item true–false test that asked about dynamic processes and identified their misconceptions (also in the Appendix). Comparison students were asked to draw diagrams and were interviewed, but due to an electronic mishap, their interviews were not available for analysis. A rater blind to condition coded the students' diagrams and interview transcripts. A subset of the diagrams and interviews were coded by a second rater ($n = 6$) for reliability. Interrater agreement was 95% for the diagrams and greater than 90% for the interviews. We also examined student projects and their explanations to help us analyze student understanding.

Second, we kept extensive records of classroom activities in the LBD classes. This was to enable us to understand the connections between what students did and did not learn and the activities they engaged in. We observed in the classroom on a daily basis and kept videos and field notes of day-to-day activities. These ethnographic observations were used to create a rich description of the classroom implementation. They also helped us understand the development of some of the children's conceptions.

THE LBD CLASSROOM: A CASE STUDY

Both to understand what the students learned and to understand the activities they engaged in, it is important to paint a rich picture of the LBD classroom context. This sequential portrait, a composite case study of two classes, is drawn from field notes

and video records and helps provide an interpretive framework for the results and conclusions of the study. As you will see, Mr. D is inventive and energetic. He knows the science and knows, as well, how to elicit curiosity, explanation, reflection, and engagement from the students. He is a master at keeping children on task, thinking science, and reflecting and collaborating, and he has excellent intuitions about the kinds of reflection and summarization students need to engage in to move forward well. He did not, however, have a deep understanding of learning through design or modeling activities. During the LBD activity, he struggled with applying his skills to promoting learning from design activity, and he struggled as well with orchestrating a sequence of activities that would allow learning from design to work well for his sixth grade students. Both his excellent skills and his struggles helped us understand some of what is important for making design activities promote deep learning. We take readers through the activities of getting started, identifying learning issues, investigation, design and construction, and summing up, pointing out along the way the strategies Mr. D used to help students were stay on track, make connections, and remember the purpose of what they were doing.

Getting Started

Students in our LBD classroom learned about the respiratory system by attempting to solve this design problem:

> You have watched a CNN special about the lung and have recently seen some newspaper articles on lung disease and organ transplants. Organ transplants are hard to come by and there is no guarantee that one will be available when needed. You are a group of socially conscious entrepreneurs, inventors, and scientists at a biomedical engineering firm. You realize that you could save a lot of human suffering if you designed an artificial lung.
>
> Plan the design of a practical artificial lung and build a model of some piece of your design.

Mr. D introduced the problem statement with a dramatic opening. He turned off the lights, plunging the room into darkness, and then in a deep, solemn voice he began talking: "I want you to think about what it was like a long, long time ago," he said, "back in the ancient times when Man had no knowledge of the workings of his body." He talked about different body systems and described the gradual process that people went through in acquiring knowledge about the body, emphasizing that knowledge came slowly and required the work of many people. As he spoke, he lit a set of birthday candles arranged in a pie tin in front of him one by one until the interior of the room was once again visible. Mr. D called the students' attention to this gradual change from obscurity to light, and he told the students,

"Our knowledge grows in the same way, one step at a time, and our understanding increases just as our ability to see within the room improves with the addition of each new candle." When all the candles were lit, he asked one student "with a good strong set of lungs" to blow them out. During this introduction the students sat silent and alert, in hushed expectancy. They were ready for a new learning adventure, and through the use of the candles, Mr. D prepared the students to learn about the lungs.

Mr. D had the students read the problem statement from the overhead, pausing often to clarify terms and check their comprehension: They were told that many people suffer from respiratory disease and need new lungs, but that lung transplants are in short supply. Their problem, as a class, was to design an artificial lung that could be used to alleviate these patients' suffering.

Next, he put students into groups and gave each group a short article relating to the lungs: one on cystic fibrosis, one about a celebrity with a spinal cord injury that left him unable to breathe without assistance (Christopher Reeve), and one a diary of a lung transplant patient. Mr. D skillfully provided a micro-lesson in research here as he pointed them to sections of the articles that contained the main ideas. After a brief reading time, he asked each group to state a couple of important facts or ideas that they had gleaned from the articles, and he closed the class by recapping the problem statement and summarizing what the class would be trying to do over the next 2 weeks.

Generating Learning Issues

The next day, to orient the students to the PBL process and the whiteboards, Mr. D put up an overhead with the whiteboard form on it and talked through the meanings of the terms in the headings of each column (Fact, Idea, Learning Issue, Action Plan). Next he went back to the problem statement and began eliciting labels for each phrase. As the students assigned the phrases to appropriate columns on the whiteboard, the teacher also asked them to extrapolate other entries from that one. For example,

Mr. D (reading):	"Organ transplants are difficult to come by." Is that a fact? (Several students said yes, it's a fact. Mr. D instructed R to write it down.)
Mr. D:	Is there a Learning Issue in that fact?
M (a student):	How are organ transplants difficult?
Mr. D:	How? Or ...?
Students:	Why ...
Mr. D:	Very good—Why are organ transplants difficult to come by, that's a learning issue.

After they had worked through the problem statement and written its components in the appropriate columns, Mr. D had them continue brainstorming about what they needed to learn, reminding them to refer to the articles they had read the day before. The students proposed a significant set of learning issues, some focused on the artifact they were to design; others on the science they needed to know to be successful, including the following:

How will they power their lung—What energy source might they use?
How will the artificial lung relate to the other systems of the body?
How will the artificial lung be different from the real lung?
How can they test the artificial lung to see if it works?
How is oxygen processed in the lungs?
How do we exhale carbon dioxide? What is the process that happens inside the lungs?
How do you get the carbon dioxide that you exhale—Where does it come from?
What will they make their artificial lung from? How durable would the material need to be?
Did they need to build something to protect their artificial lungs as the ribs do in their own bodies?

By the middle of the second day, the students had generated an impressive list of learning issues. Some were focused on structure (how will this be different), but other learning issues showed that they had begun to consider systems concepts, such as relations with other systems, and others asked about function and behavior (where carbon dioxide comes from, how it is processed).

Self-Directed Learning (Investigation)

Next on the agenda after generating questions was first attempts at learning their answers (also on Day 2). Mr. D introduced some resources, showing students a table piled with texts and other print resources. He singled out a few of the books, pointing out characteristics such as "this one has some interesting experiments, that one has good drawings of the lungs and respiratory system, and if you're interested in diseases of the lungs, you might take a look at this third one." Finally, he reviewed the learning issues on the board and turned the students loose to begin self-directed learning. Students worked in small groups using the resources available to attempt to answer the questions they'd generated. Each group chose a subset of the learning issues to explore, based on the interests of the individuals within each group.

As they worked on their investigations, Mr. D also introduced the students to four multimedia workstations with online resources. *BodyWorks* (SoftKey Multimedia, 1995), *ADAM* (1994), and *The Visible Chest* (Hmelo, 1986) provided the students with opportunities to explore basic information on the structure and function of the respiratory system. *The Way Things Work* (MacAuley, 1994) provided examples of different kinds of pumps that gave students some ideas of the mechanics involved in moving air. Case libraries we authored included examples of artificial medical devices such as a heart–lung machine and an artificial membrane.

The teacher moved around the classroom to check on student progress and questioned students to help them move forward, locate resources, and use computer programs. Over the next 3 days, students used the resources to begin to answer the questions generated earlier. One group read about scuba equipment and noticed the pressure regulator; another group found the piston engine and made the analogy between the motion of the piston to the motion of the diaphragm; another group found information about oil wells and considered the nature of the pumping action.

Back to the Whiteboards for Review and Update

Each class period began and ended with a review of the whiteboards. This was an important mechanism for students to share what they had learned. As students reviewed what they found, some new issues came out—J said they needed to know the difference between a normal and an abnormal breath, so they would know "what's the limit to go to, and not to go to" with their artificial lungs. They wondered if their artificial lung would have to be the same size as a real lung, or if it might be larger. P remembered from the article about Christopher Reeve that the C2–T12 vertebrae in your backbone had a lot to do with breathing, that they exerted some sort of control over the muscles—she found a second reference to this in one of the books. As they talked, they debated whether to include items under facts, ideas, or learning issues. Mr. D often guided them to see how an entry in one category led to a related entry in another category, so they began to see how one fact leads to another idea, or a learning issue, for example, or how a learning issue gets turned into an action plan. They generated many more questions that they agreed they would have to investigate if they were to design a real artificial lung:

What is the difference between a normal and an abnormal breath?
Do the components of the artificial lung need to be identical or at least similar to the parts of the real lung?
How are the C2–T12 vertebrae in your backbone related to controlling the breathing muscles?

What about the different sizes and lung capacities of people? Not all people are adults.
How will the artificial lung would have to be adapted? Will it have to be custom made for the patient?
How they would get an average lung capacity, they wonder.
Should the artificial lung be biodegradable, or should it be permanent and re-usable? Should they bury the person with the article lung, or remove it for re-use?
What would happen in an airplane, when the pressure changes, somebody wonders, to the person using an artificial lung?
What about people with asthma? How would an inhaler affect the artificial lung medications?

Whiteboarding helped students organize their class time and focus their research. They started each day with a review of the problem and a review of the whiteboards they had generated. They added to the whiteboards at the beginning of class whenever it was appropriate. They ended each class by returning to the whiteboard again—reviewing, updating, or recreating their lists of facts, ideas, learning issues, and action items. Often, these whiteboards helped the students reflect on what they had learned and struggled with during that class period. A major purpose of returning to the whiteboards was to keep students focused on the purpose of their investigative activities. Another purpose was to help them integrate the many things they were doing and hearing about.

Hands-On Investigations

In addition to using the books and multimedia resources for information about the respiratory system, the students engaged in several hands-on investigations designed to help them answer the questions they had posed about specifications for their artificial lungs—how much air they would need to move and how that would change with different activities and for different-sized individuals. In one investigation, Mr. D introduced the students to commercial spirometers, clear plastic tubes with a ping pong ball inside and a flexible tube that the user breathes into. They measure how much air one can inhale during a breath. Spirometers are used by hospitals to encourage patients who have just undergone surgery to inhale more deeply. The students took turns at trying out the devices, and then Mr. D set up an experimental activity in which some students ran up and down the hallway, checking their lung capacity with the spirometers before and after exercise, while others measured resting lung capacity. When they had collected enough data and marked it on lab sheets, students presented their results to the class and compared to see who moved the most air while breathing: big students or small students, resting students

or running students, girls or boys. As they worked through these comparisons, Mr. D elicited more learning issues; for example, who seems to have the greatest lung capacity, and why?

Making Connections

Although the students had collected a lot of information during their investigative activities, it was in isolated fragments. Following the hands-on investigations, Mr. D brought the class together as a group to help them make sense of what they had just experienced and to connect it to their design challenge. He had students think about the amount of air their lungs take in. He asked them what it means when that amount gets larger or smaller than normal. "What happens when you're sick?" he asked. "Or when you're injured? What about when you're doing heavy exercise? Is it different for a person who's in really good condition, like an athlete?" Soon the students were calling out their own "What if?" questions, and thinking of other circumstances that might affect an individual's lung capacity either temporarily or permanently. These questions were designed to help the students think about functions and behavior.

Mr. D used a variety of open-ended questions to get information from the students, stimulate their thinking, and help them make connections between their investigations and their design challenge. He was able to get the students to talk implicitly about function and behavior through his questions (What happened? What's the purpose of?), but most of their spontaneous talk focused on structure.

Getting Ready for Design

On Day 6, students began designing. They had generated questions, had done reading and hands-on investigations to begin to get answers, and it was time to apply what they had learned. Before students began their design activity, they discussed what they might need to build their artificial lung. They offered suggestions that included such materials as broccoli, straws, balloons, and sponges. This was the beginning of a pattern in which students focused on designs that look like the lung rather than work like the lung. Many of them did, however, move on toward more function-oriented models.

An engineering professor, Dr. A, came in for 2 days to give a lesson on engineering design and to help the children get started designing. She talked to the students about the process of design, and she showed them a handout she uses in her own college-level class. The handout portrayed an abstract model of the design process, and the students listened politely but did not seem to grasp what Dr. A was talking about. This model showed the lifecycle of a boat and started with identifying the problem, generating concepts, and initial design through disposing of the

ship. Noticing their confusion, Dr. A went to the chalkboard where they had listed Facts, Ideas, Learning Issues, and Action Plans. "This is great," she told them, "but it's a lot of information to work with. It will help you work better if you select a few key issues and concentrate on them at first, then when you're satisfied that you've learned enough about those issues, you can come back here and select another one or two." With her guidance, they generated a number of subissues:

How will the artificial lung move and look real?
What about the pressure inside of the lung?
How does oxygen get into the blood?
How much oxygen can the lung take in?
How much oxygen does a person need?
How can we be sure the artificial lung takes in that much oxygen?
How might bacteria affect the lung?
When would the lung need to be replaced?
How much oxygen stays in the body?

These subissues were more specific and pragmatic than the issues the students had raised earlier. Many of them considered behavioral and functional issues as well as structural issues. Dr. A encouraged students to choose a few items from the list to focus on and then told them they needed to decide who would find out the information. She tried to get commitments from individual students to take responsibility for particular learning issues. This was the first time they were given specific direction in how to come to terms with the mass of information and questions they had generated. Finally, she suggested they break into small groups and try out some of the materials available. There were piles of balloons, straws, plastic tubing, and tape, as well as a collection of empty 2-L soda bottles. Students had also brought in clay and a motorized construction set.

Designing

The groups had different ideas about how to proceed: some groups began by looking for models to copy; others by experimenting with the materials available (e.g., balloons, clay, electronic construction toys). One boy showed his group how to build a model of a lung with a diaphragm that he had done in another class; a pair of girls saw this and, recalling that they had seen this same design in one of the books on the research table, they found the book with its written instructions. Thus they began their design process by copying an example. The first group asked Mr. D to cut the bottom off a 2-L bottle. They then stretched a balloon across the opening, holding it in place with a rubber band. They inserted straws into the openings of two additional balloons and sealed the edges with tape. With more tape they connected

the other ends of the straws to a single straw to form an inverted Y. The two balloons were inserted into the bottle and the mouth of the bottle was also sealed with tape so that air could only move in and out via the single straw that protrudes from the top of the bottle. When the group leader tugged on the stretched balloon at the bottom of the bottle, it caused air to be sucked into the lung balloons inside the bottle through the straws, and the balloons inflated. When he released the stretched balloon "diaphragm," the lung balloons inside the bottle deflated. This nicely demonstrated the function of the diaphragm, and other groups moved to duplicate this model. Although the task was to design an artificial lung, this was overwhelming for these students, so they transformed the task into a modeling task that they could manage.

Dr. A noticed that several groups were merely imitating the aforementioned model, and she sat down with one cluster of students to discuss their options. With her guidance, the group went through several "drafts" of their design during the class period. Their model was at first very much like the aforementioned one, but it became progressively more complex and accurate. Dr. A's direct intervention and facilitation with one group helped that set of students question their ideas more closely and follow up on the effects of their design hypotheses.

Building Models

On the 2 designated construction days, Mr. D had each of his two classes for 2-hr blocks. Before he turned them loose, he conducted a lengthy review session, starting with a clean chalkboard and using a student scribe to write down ideas. For nearly 1 hr, they worked on recreating the whiteboards, generating anew the Facts, Ideas, Learning Issues, and Action Plans they had compiled over the past week. During this review activity there was a lot of repetition, but also a good bit of reformulation and synthesis of ideas as the students had to put their new knowledge into succinct words and phrases for the scribes to write on the board. All of the ideas, trials, new information, and hypotheses recycled during this activity.

The students continued with the designs they began working on the day before and modified them, often based on the teacher's very pointed questions about form and function. A few students kept moving back and forth between the CD stations and the worktables, checking information as they built their models.

The groups eventually began to diversify their design ideas. One group decided to make a motorized diaphragm for their lung, using the electric motor from the electronic construction set that one boy brought from home. Across the room, B dreamed up a variation on the soda bottle design in which he would submerge the lung balloons in an oversized beaker of green water and use the pressure of the water to inflate and deflate the lungs.

During model building, most of the design ideas were shared informally as students looked around the classroom and showed other groups design features that

they were particularly proud of. Most of the students decided to focus on constructing a model that would move air in and out of the lungs. This is possibly because of the perceptual salience of this part of the respiratory system, possibly because of the affordances of the materials we made available (e.g., straws, balloons). Some groups were influenced by the article they had read about spinal cord injury and expressed concerns about the need to power the system. The group that had made the motorized diaphragm talked about the need to control the system and provide feedback to the controllers. Many groups acknowledged that gas exchange was needed, but this was often through attaching objects to represent alveoli and blood vessels on the outside of the soda bottle.

One group seriously considered how to implement gas exchange. They built a model with straws that represented tubes that would go into arteries and veins in the arm (much like a heart–lung machine does!) and then would get oxygen into the blood through a balloon membrane. They knew, however, that they had not accomplished the goal of designing something that would work. When Dr. C met with them, they commented on how their design "really wouldn't work." When Dr. C asked them why, a discussion of the properties of membranes and diffusion ensued. They clearly were thinking about this important issue, but they did not discuss what they were thinking with anybody else in the class, and their ideas never diffused around the classroom.

Student Presentations

On the day of the presentations, Mr. D began with a review of the problem statement. He then put up a few transparencies with questions to guide students through a critical review of projects and to remind them of appropriate behavior. Rereading the problem statement allowed Mr. D to remind the students that part of their task was to "design and market" an artificial lung and to present their solutions to the board of directors. He also reminded them that the reason for building the artificial lung was to solve the current problem of a limited supply of available lungs for patients who need transplant surgery. This recapping of the entire problem statement pulled the 2 weeks together again and set the tone for the presentations. The students reviewed the various resources they used, naming the multimedia stations, mentioning the books they used, and also pointing out that Dr. A had come in to help them.

Finally, the students presented their work. Each group demonstrated their artificial lung models and explained their functions, as well as the design decisions they made along the way. The class meetings for these presentations were quite rich in detail, and Mr. D used these as vehicles to promote further learning. In their presentations, students frequently used the technical language of the respiratory system, particularly the language of structure. We describe two of them in detail.

The first group, S and his partner V, a female student, did their demonstration together. S began: "This is our artificial lung, this tube is the trachea, the plastic

wrap is the pleura, this tube is where the carbon dioxide goes out, the sponges are the alveoli and the red dots are the capillaries." Mr. D, who had his attention diverted with another group's question, asked the group to repeat their description. V spoke this time, repeating the identification of the component parts of the lung model. S gently prompted her when she hesitated over one, but in general she spoke very smoothly. When she stopped, S added, "This balloon (on top of the bottle) represents oxygen coming into the lung." Mr. D asked, "Okay, could you explain some of the design decisions you made?" S looked a bit taken aback and quickly motioned to V. V looked at Mr. D, and another student asked, "Why did you choose the plastic bottle instead of the balloon?" V said, "because it would work better." Somebody else asked, "What are those little things in the bottom?" V said "They're supposed to be the filters," and S added, "They're the oxygen molecules but they just kinda shot out." Originally they had tried to attach these bits of sponge to the exterior of the lung balloons to represent filters and oxygen molecules, but the balloon fragments kept falling off and now littered the bottom of the bottle. "Okay," said Mr. D, "so you're saying what, you've maybe got some design problems that you're just going to have to work out?" "Yeah," V agrees. Dr. C asked about the purpose of the balloon on the top. S said, "It represents oxygen going in." Dr. C pursued this point: "How is the oxygen going to get in there?" S and V said together, "When you breathe in." Mr. D pointed out, "But the person can't breathe in by themselves, they're sick or injured." V quickly changed her answer: "The diaphragm."

The two adults (Mr. D and Dr. C [Cindy E. Hmelo], an expert on the respiratory system) tried to facilitate the students' explanation of how the artificial lung would take in and expel air, because the students' model had not taken into account the need to power the diaphragm. Mr. D asked, "Okay, so are you gonna attach, um, the diaphragm, the person's diaphragm ... Dr. C, so is it gonna use the person's diaphragm then, is this [the students' model] just the lung piece of the respiratory system?" This hazy explanation suited V, who quickly agreed: "Yeah." Dr. C asked, "How come you decided ... so how big is this compared to a real lung, is this bigger or smaller?" S knew this answer: "It holds 2 liters, and an adult's lung holds 3 liters." V confirmed this: "So it's smaller than an adult's."

The next group to make their presentation was T's group. They had a 2-L bottle lung also, and a poster with drawings, which they took from the computer CD stations, of the respiratory system. T explained their model: It has two balloons inside a plastic bottle to represent the lungs, with a plastic tube for the trachea, and sponges for the alveoli. Then T asked for a volunteer to breathe into their tube. When air was blown into the tube, the lung balloons inflated. But Mr. D did not let the group off with such a simple demonstration. He began questioning them: "But the person cannot breathe, so my question is this—how are you going to get the air into the lungs?" "The diaphragm," one of the students said, rather automatically. "But are you using the artificial diaphragm or the real diaphragm?" Mr. D won-

dered. "The artificial diaphragm," T answered confidently. "And if that's the case, when I pull down on the artificial diaphragm are the lungs going to inflate? Because if the person could breathe then we wouldn't have the need to create an artificial lung ... " With this last statement, Mr. D reminded the students that they have to remember what their original goal was. He continued: "When I pull on this are these lungs going to inflate and deflate?" (Yes.) "Okay, I need to know what's what and how it functions," he insisted. "Because it seems to me that you are expecting the person to inhale on his own, but if the person could breathe then we wouldn't need this."

Satisfied that the students are fully focused on answering serious questions, Mr. D resumed his questions about the group's model: "Where does oxygen go?" D, pointing at the model as he talked, explained, "It goes through the alveoli, passes through, uh, this, which is permeable, then it goes through the capillary network and ... " As he spoke, D got help from another teammate, who prompted the sequencing of events for him. T worked through it, using all the vocabulary that the students before him used. Mr. D focused on the "permeable wall" for a moment, asking them how they have you provided for the oxygen to pass through this wall in their model.

The students got confused as they tried to answer his questions about the transfer of oxygen from the lungs to the alveoli and into the blood stream. "How does it happen?" Mr. D kept asking, but they were stumped. T said something about using the heart from the real person, because this model doesn't have a heart. "And where does the carbon dioxide come out?" Mr. D asked. T said, "The mouth." He kept pushing the students to explain their thinking, grilling them on the details of their own model and of the real respiratory system. He reminded the rest of the audience to listen. He managed to get them to mention carbon dioxide: "What is carbon dioxide tension, gentlemen?" he asked. H said, "Carbon dioxide tension is the pressure that carbon dioxide has on the capillaries ... and it pushes it into the alveoli and it goes out the trachea." Mr. D asked him to repeat this explanation, then asked, "Is this something that all gases do?" "Yes," said H. "So they go from an area of what to what?" Mr. D prompted, rephrasing the student's explanation into more precise terminology. H responded, "They go from an area of high concentration to low concentration." "Okay," Mr. D continued, "Why is the carbon dioxide moving from the red blood cells into the capillaries then?" H said, "Because the carbon dioxide gets crowded in the red blood cells, and ... uh ... ." Mr. D prompted him: "and it's finally reached an area of ... ." H finished the statement: "... of low concentration." Although it is not clear just how deeply the students understood what they were saying, it is clear that they were appropriating the language of the domain.

The questioning process during these presentations was another opportunity for learning. Mr. D encouraged the students to use the vocabulary they had learned to

explain their models, and he asked them some very hard questions. He elicited explanations of processes that perhaps were not really clear in students' minds before the presentations. He also orchestrated a good deal of repetition, so that both speakers and audience got engaged in discussions of the scientific content. During the presentations, the class was attentive and engaged, thinking about the difficult questions and posing some of their own. They spent this time searching for ways to explain, justify, and defend their positions. When the students were hesitant, or when his questioning caught them in an error, Mr. D was careful not to characterize these lapses as failures, but rather to portray them as natural and expected events in the process of doing science. He cast the students in the role of scientists with work in progress, getting feedback from fellow scientists, able to go on the next day to continue dealing with the problem. Whether they actually revisited the problem did not matter; the point was for them to understand that scientists do not just give up when a problem arises. This was a very important part of this lesson and of Mr. D's overall style of instruction.

Final Review and Summary

The final day was set aside for pulling things together. Mr. D told the students that the lung challenge had been an especially hard problem, and he wanted them to think about all of the things they did—the research, CD stations, books, and all of the resources. He asked them to think about the respiratory system and all that they learned about breathing. He asked them to think quietly to themselves for a few minutes, and maintained silence while they thought; then he asked them to "network" with somebody nearby, talk about what they have learned, share their knowledge and their ideas. The students began to talk, and Mr. D made sure every student was included in some group for this discussion phase. He suggested they get paper and pencil to take notes, because they would be discussing so many ideas.

Mr. D opened the whole-class discussion by asking a question: "Why does your body need more oxygen when you are exercising?" The students told him that you're burning more oxygen when you're exercising, and one compared this to a car that uses more fuel when it's going fast. Mr. D liked this analogy and questioned the students a bit more, prompting them to see that oxygen is a kind of fuel for the body, just like gas is a fuel for the car, and provides the energy needed for exercise. This question was designed to help students integrate their ideas and make connections between structure and function (though issues regarding behavior are not often raised).

Mr. D tried to enhance student reflection by creating links to their personal interests: "Are there any singers in here besides me? ... Maybe you've heard singing coaches say, 'Sing from your diaphragm.' What does that mean?" The students talked enthusiastically, several offering connections to personal examples, about what it might mean to sing from the diaphragm rather than from the throat. The

room got a bit noisy and Mr. D suddenly said, "Okay, stop for a minute, here's what I want you to do: I want everyone to take one really deep breath, and then start talking, and talk as much as you can until that breath is completely gone, but don't take another breath, just stop talking when that one runs out. Okay, ready? One, two three—inhale (he inhaled deeply and noisily), now GO!" The room erupted in noisy chatter, students were all talking furiously, some actually did stop as their breath ran out, but more just kept breathing again and talking. Mr. D cut them off after about a minute and went on: "Did you feel it? Could you feel the air just leaving, and after a bit you were forcing your talk and it was just way up here in your throat?" He led them to reflect on what they learned about the diaphragm, its movement relevant to inhaling and exhaling, and the relative roles of oxygen and carbon dioxide in this process.

Next, the students explained the process from the beginning of a breath to exhalation. Mr. D had them name the parts of the system and draw on the board. He continued questioning and using open-ended prompts with the students, constantly urging them to be more specific, elaborate their ideas, use the new vocabulary, and explain in depth.

They stumbled a bit over the gas exchange part of the explanation, and Mr. D went into an impromptu analogic demonstration. The students kept saying that oxygen goes into the blood and carbon dioxide comes out, but could not answer his repeated query of "Why? Well tell me this," he said, "Do gases like to be crowded up into corners?" "No," the students said. "Okay, so you're breathing in, and each time you do that, do the lungs get rid of all the oxygen? No? So you're saying, there is some kind of oxygen residue ... but why?" The students looked at each other and at him, shrugging their shoulders or waiting expectantly. Mr. D did a demonstration with the students to help them understand why gas molecules go from a high concentration to a low concentration by using the analogy of a crowd of people.

At this point S asked, "What would happen if the body didn't get rid of the carbon dioxide?" Mr. D responded: "That's a really good question, and I don't know what the answer is. What do you all think? What might happen if the body does not get rid of the carbon dioxide?" The students were fully involved, so they start calling out lots of (sometimes outrageous) ideas: The body might shut down, the blood might clot, it might turn black and blue, or the body part might die. Mr. D told them these were excellent suggestions, and he himself would like to find out the answer to S's question. He was comfortable showing the students that his own knowledge is far from complete and that he was willing to learn along with his students.

ANALYSIS: INTENDED VERSUS ENACTED CURRICULUM

Although the products being constructed by the students were not as complex as we had hoped they might be, the activity, as modified by the teacher and students, was a

manageable problem for the sixth graders, and it indeed seemed to provide a vehicle through which the students could learn about the respiratory system. Looking back on this experience, we can identify both good practices and missed opportunities in this sequence of activities. The teacher was an excellent facilitator who could draw students out. On the other hand, neither he nor we understood completely the affordances of designing and modeling well enough to use the activity's full potential for promoting learning. Nor was he completely comfortable with the new practices we wanted him to facilitate. We compare the intended and enacted curricula to each other in this section, focusing on those aspects of the enactment that allow us to make predictions about what students might have learned and on those that allow us to make recommendations on how to productively facilitate learning from design activities.

Scaffolding

The teacher was a master at providing much of the scaffolding necessary for inquiry and knowledge building. Using PBL's whiteboards as his anchor, he helped students generate questions and investigate to answer them using available written resources as well as through experimentation. He used the whiteboard, as well, to help students plan and monitor their activities. His questions to students often prompted the thinking he wanted students to be doing. His dramatic opening was aimed at helping students understand that learning is incremental and that each new answer helps to light the way to new questions. His questioning during presentations helped students engage in the discourse of science. His closing reflective activities helped students pull together what they had done and extract things they had learned.

On the other hand, some scaffolding that would have helped was missing, particularly the kind of structuring of the activity that the teacher could have provided for the students that would have allowed them to be more successful designers and modelers. Specifically, there was no scaffolding provided to help students plan the design of their lung models based on what they had learned. Nor was there scaffolding to help them debug and explain their models.

Integrating Doing and Reflection

The teacher did a remarkable job of keeping students focused on their learning and not just on completing a project. He used the whiteboard as an external memory, helping to recontextualize the students each day. Either they looked at the whiteboard from the day before and used it to remind themselves of what they were doing, or they generated a new whiteboard as a way of summarizing and organizing

their thoughts. This simple activity was intended to keep students connected to their end goal (designing an artificial lung), to the investigations they needed to do to get to that goal, and to the progressions in their knowledge and inquiry. Whiteboarding drove the activity forward, advancing reflection of many different kinds—planning, monitoring goal-oriented activity, monitoring learning, retrospectively extracting from previous experience the important points and the important skills, and bringing it all together.

Iteration Toward Understanding

Iteration toward understanding was more mixed. Schauble et al.'s (1991), Linn's (1995), and Kolodner's (1997) recommendations were that students would need to iteratively improve their models to come to a good understanding of the lungs and respiratory system. Indeed, the students did some important and powerful iteration. They began by generating questions and investigating to answer them. Their first attempts at understanding came from those activities. They got their first ideas for models based on the understanding gleaned from investigations. Before they began construction of physical models, they reviewed as a class what they had learned, and the teacher attempted to help them expand their understandings and connect what they had read to the world around them. They then worked on construction of physical models until they got them to work, sometimes generating new questions along the way and going back to the resource materials to look up what they needed. They presented their models to the class, had a classwide discussion—again raising interesting new questions and summarizing what they had learned. The teacher helped guide their discussions so that they would integrate together and expand on the bits and pieces they each knew. All of this was a good beginning and a match to what Linn's (1995) knowledge integration work implies is needed to make sense of how things work.

Unfortunately, however, the students stopped at the point where each had a first partial working model. The issues they needed to address to understand respiration and the respiratory system were just beginning to become visible to them at that time, and they were just beginning to be able to talk the language of science and systems cogently. Discussion about that thinking continued in the last day's reflection, but students did not have an opportunity to apply their ideas in a new situation. They had no opportunity to continue adding to their fluency. This, we believe, was the major deficiency in this implementation and the source of other deficiencies discussed later. Students never had the experience of putting their ideas to work fully, enough to experience and explain failure. Our intention had been that students would design and build a model, test it and find a need to learn something new, discuss their results with the class (in the process suggesting explanations and raising new issues), and then

iteratively make their models better—in parallel with refining and increasing their own understanding. Unfortunately, these multiple trials in building and testing models did not happen.

Design and Modeling

Management of the design and modeling components of the activity was mixed as well. Our intention was that the design challenge would provide motivation for learning the underlying science, focus to student investigations, and a venue for putting what they learned into practice and testing their understanding. Indeed, the students did seem to be motivated by the design challenge. The challenge, plus the teachers' use of the challenge to provide focus, kept students engaged throughout the 2.5 weeks of the design experiment. As well, students seemed to have a purpose in their investigations, and the teacher did an excellent job of using the design challenge to focus classroom discussions. On the other hand, the design challenge, as orchestrated, was too complex to provide a venue for applying what they had learned.

The intention had been that although students would not be able to achieve the challenge, they would be able to design and build models of some parts of an artificial or real lung, and indeed, some of them began to do that. Their models tended to focus on some aspect of the natural lung, looking at what it takes to carry out that function, and assuming that an artificial lung would have to carry out the same function. Some of their models carried out some simple function of a lung—usually filling the lungs with air. That some of their models focused on implementing some function and not merely on making something that looked like a lung was an excellent and promising beginning. But not everyone constructed or designed a working model. Even those that were working models were generally disconnected from the rest of the respiratory system. For example, though several had diaphragms in their models, few of them thought about how they would get their diaphragm to move and what mechanisms would be needed to get it started. None of the students had completely thought about what would happen to the air once it was inside in the artificial lung.

On the other hand, discussion during their presentations began to make students aware of these issues. It seemed to show that they had learned some things about the workings of the lungs and respiratory system and that they were capable, with prompting, of thinking about their models at a more sophisticated level than what they had built. It would have been interesting to go on with this activity another week and through two or three more iterations of construction, testing, and revision interleaved with classroom presentations and reflective discussions to see what kind of sophistication and fidelity they would have brought into their modeling.

Another problematic aspect of this implementation was the poor connection between the research they did early and the modeling they did later. The design challenge seemed to give students the motivation tc ask questions and investigate, and seemed to give them some focus for their investigations. It became clear, however, when Dr. A began helping the students to design, that the connections had not been made sufficiently. Students' research had been focused on big issues but not on the details they needed to understand to be able to design and build something that could work. The design challenge had not helped students sufficiently focus their earlier investigations as intended.

Also problematic was the lack of explicit connection between the design challenge presented to the students and the modeling activity they actually did. It was ambiguous to us, and to the students as well, whether they were constructing a miniature artificial lung, a model of an artificial lung, or a model of a real lung or part of the respiratory system. In the scenario described earlier, there were missed opportunities to discuss with the class what they were doing and the role that modeling plays in design. We conjecture that if the class had had that discussion and each group had been clear about the purpose of what they were building (a model of the diaphragm getting air into the body, a model of a diaphragm-like pump), they might have been able to be more focused in their construction, in generating and answering new questions (learning issues), and ultimately more successful. Had that opportunity been taken advantage of, students would have had a chance to be introduced to the process we call modeling; they could have had an interesting science process discussion and perhaps learned about modeling as something scientists and engineers do as a method of investigation.

Getting to Function and Behavior

Neither classroom discussion nor experience focused as explicitly on function or behavior as it might have. But the real issue, here, we think, is that students did not have enough chances to iteratively refine their models to get to the point where discussion about behavior was appropriate. Their largely appearance-based models suggest that students focused largely on the structural aspects of the design task. Although they talked about the function that the components of their designs were supposed to accomplish, most of the models were static and had no way for students to demonstrate the functions and causal mechanisms that were involved. Additional iteration would have allowed the students to focus on constructing working models, as was the pattern in Penner et al.'s (1997) study. Such revisions would have promoted more focus on function and behavior. After the first time through, they discussed structure, they discussed the functions their models needed to carry out, and they began to discuss the kinds of connections their pieces of the system needed to have to other parts of the system. But only by following through to itera-

tions of their models that took those connections into account would they have had reason to discuss in detail the mechanisms underlying how lungs work.

Roles of Collaboration

We had expected two kinds of collaborative activities: (a) that small groups of students would work together on investigations and on construction activities and (b) that the whole class would get together as a group once or twice each class period to generate questions, share what they had found, recap, plan, or review. Indeed, both types of collaboration happened. But a third type of collaborative activity happened, as well, that holds promising potential as a formal vehicle for promoting learning. This was the more organic or informal discussions that class members had with each other across collaborative work groups while engaged in small-group work. Students helped each other use the computer resources and make suggestions to each other about how their models might look like and work. One student's idea, at the beginning of their modeling activities, became an idea for other groups to copy and then adapt. It served to bootstrap the groups that had difficulty getting started. Children's discussion with each other during construction helped some students move the next steps forward.

Integrating these kinds of activities into the formal system of LBD activities might help alleviate some of the confusion in the classroom, might promote connections to be made between the different activities students engaged in (design, modeling, investigation), and would allow students to provide scaffolding for each other. In our current work (Kolodner et al., 1998), we have integrated these kinds of activities into the formal system of classroom activities. In our current LBD classrooms, students present their ideas to each other in "pin-up sessions" before they begin construction, and they gather together for "gallery walks" several times during their construction and testing activities—after each group has completed a first iteration and third iteration, when any group needs help, and when any group has something important to show to the class. The informal discussion between groups is still a phenomenon in the classroom, but by adding in the formal presentations, all students have a chance to get ideas from each other and question each other. All get a chance to use the science concepts they are learning in explanations to others, and the opportunities for bringing things together and integrating knowledge are increased.

RESULTS: WHAT DID STUDENTS LEARN?

To interpret the successes and limitations of our approach, we need to consider first what we could have expected students to learn from the enacted activity.

We look at the products they created and the classroom discussion topics to make those predictions.

The models that emerged from this activity were, for the most part, models of some part of the human respiratory system rather than serious attempts at producing artificial lungs. Because the activity was so complex, because students had so little opportunity to iteratively refine their models, and because materials didn't afford coverage of all issues, major portions of the systems interactions were lost. For example, oxygen transfer occurred mysteriously through sponge/alveoli and returned via an equally mysterious process. The prototypical project was made out of a soda bottle to represent the chest, balloons or sponges to represent the lungs, and straws to represent the airways. Some of the children included water to represent the blood–air barrier. Despite learning issues that addressed deeper levels of knowledge, most of the models were simply collections of structures. It was promising, however, to see that even these structurally focused models had some simple representations of function embodied in them. For example, the students generally included a hard shell to protect the lungs, much as the ribcage does. Their representations of the blood–air barrier, though quite superficial, suggest that they acknowledged that gas exchange was an important function of the respiratory system. A small number of groups made clearer connections to function and behavior. One group of students used a motor to drive the movement of the diaphragm and noted that, for their artificial lung to work correctly, they would need sensors to determine when there was enough air. These students were clearly making connections among structure, function, and causal behaviors as well as the systems concepts of feedback and control.

Discussion in the classroom was based on the design and construction activities students had engaged in. Thus, its primary focus was on structural parts of the lungs (e.g., the alveoli) and the functions they carry out, but not about the behaviors that allow them to carry out those functions. It was also likely that students would understand that the diaphragm is part of the respiratory system and that it is responsible for moving air into the lungs, as there was much discussion of the diaphragm.

Based on the classroom enactment, it seemed likely to us that students would understand that systems have structural parts that carry out functions. It seemed likely, as well, to expect that students would understand the structural parts of the lungs and the functions of each. Their design activities might have afforded the beginnings of an understanding of the connections between the parts, but probably not a deep understanding of their causal connections (behaviors), as they never engaged in construction or discussion aimed specifically at understanding causality.

To find out what they knew about the lungs and respiratory system, we analyzed pre- and postconceptual understanding tests, student drawings, and student interviews. To examine whether the LBD had had an effect on the class, we administered a 12-item true–false test of conceptual understanding of the lungs and re-

spiratory system to all the students (comparison class and LBD classes) as pre- and posttests (shown in the Appendix). The results are shown in Figure 2. The children in the LBD classroom increased their scores from pre- to posttest, $F(1, 32) = 6.23$, $p < .05$, whereas the comparison students did not, $F(1, 12) = 1.76, p > .15$.

Pre- and posttest results suggest that the LBD students increased their understanding of the system somewhat, but they are only minimally informative in understanding how the children's mental models of the respiratory system changed. Examining the children's drawings and their responses to clinical interviews provides a richer picture of the students' understanding and shows that, indeed, LBD students were beginning to view the respiratory system more systemically.

Before and after instruction, we gave students in the LBD and comparison classes an outline of the human body, and asked them to draw the respiratory system. These drawings allowed us to determine how local or systemic the students' thinking was. A holistic coding scheme, shown in Table 2, was developed to analyze the diagrams. Five types of models were identified from the diagrams that the children drew. The models became increasingly systemic and sophisticated from the lowest model to the highest, showing more interactions among parts and with other systems (such as the brain) at the higher levels.

Table 3 shows the results of the mental model analysis of the children's diagrams, and Figure 3 shows changes in the level of sophistication of their models.

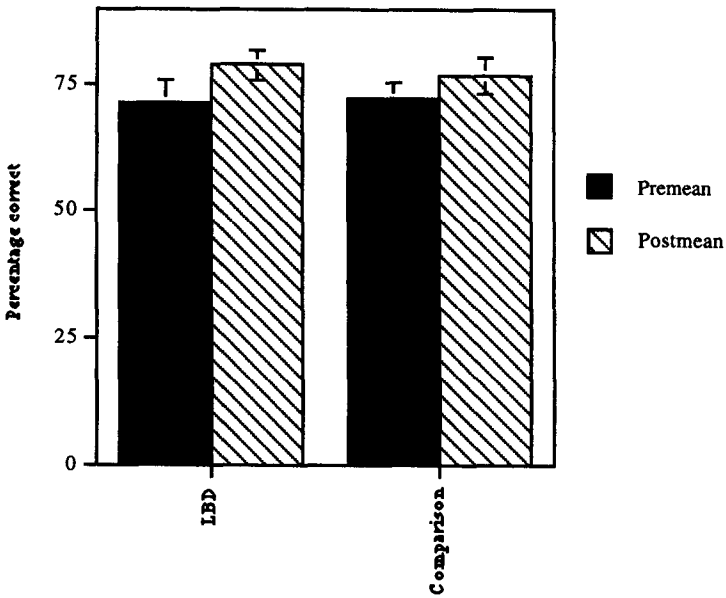

FIGURE 2 Conceptual knowledge scores at pre- and posttest.

TABLE 2
Mental Model Coding of Students' Diagrams

Model	*Description*
Model 1: Lung as a bag	Shows some hollow structures in the chest but there are no connections to other systems. There is no evidence that the lungs do any processing. This is a very limited model with only some superficial structural features.
Model 2: "It's all in the chest."	Pictures of the lung with dots that represented the air spaces and blood vessels. It was not clear that students holding this understanding were aware of how the different parts of the system were related to each other.
Model 3: Connected chest	Included connections between the different structures that they drew. It was clear that the air spaces were an integral part of the lung.
Model 4: Systemic with misconceptions	Include connections to the rest of the body such as the brain and peripheral blood vessels. Indicates some misconceptions, most commonly that abdominal organs were part of the respiratory system (the children conflated the role of air, food, and blood).
Model 5: Systemic model with no misconceptions	Includes connections to the rest of the body such as the brain and peripheral blood vessels. Most complete and correct.

TABLE 3
Results of Mental Model Coding of Students' Diagrams

	Comparison		*Learning by Design*	
Model	*Pre*	*Post*	*Pre*	*Post*
1	8 (61.54)	2 (15.38)	3 (16.67)	0 (0.00)
2	1 (7.69)	3 (23.08)	8 (44.44)	5 (27.78)
3	1 (7.69)	7 (53.85)	3 (16.67)	8 (44.44)
4	2 (15.38)	0 (0.00)	2 (11.11)	1 (5.56)
5	1(7.69)	1 (7.69)	2 (11.11)	4 (22.22)

Note. Percentages are shown in parentheses.

The pretests for all students (LBD and comparison class) show that most had Model 1 and 2 diagrams. This indicates that the students knew that the lung is composed of parts, but they did not have a good understanding of how the structures were related to each other. At posttest, the comparison classroom had Models 2 and 3 most frequently, with only one having Model 5. While the LBD students' understandings were also clustered around Models 2 and 3, no LBD student still had an understanding consistent with Model 1 (the lowest), and several students had understandings at Levels 4 and 5, a reliable improvement for LBD students (Sign Test, $p < .005$) but not for comparison students ($p > .25$). Results indicate that the

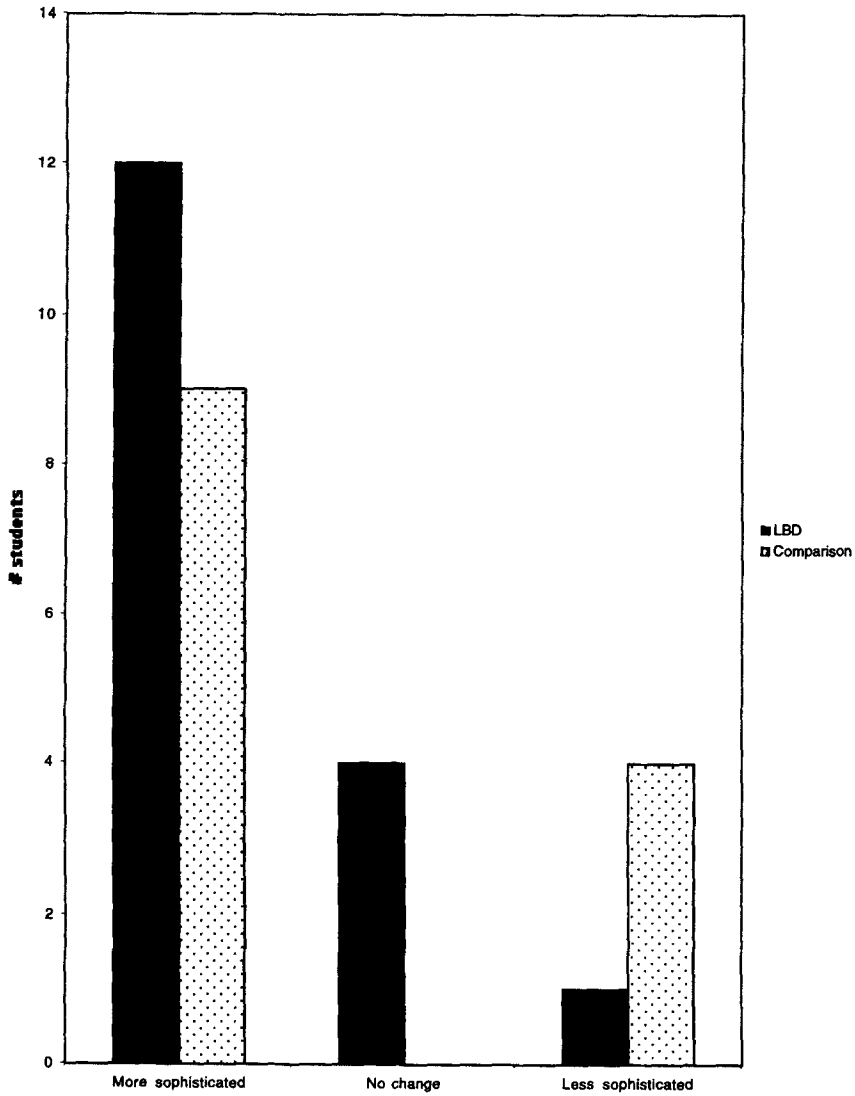

FIGURE 3 Change in model sophistication from pre- to posttest by group.

LBD students indeed had a better understanding of how the structures were related to each other and viewed respiration more systemically.

Figures 4 and 5 show an example of that change. In Figure 4, we see Learning by Design student E's drawing at pretest, a Model 3 understanding showing only a few structures involved in breathing strictly in the chest. At post (Figure 5), her diagram includes additional structures and more systems, including peripheral blood vessels and brain, indicating a Model 4 or 5 understanding.

To dig deeper into what students had learned, we conducted pre- and postinterviews in which we asked students about the respiratory system and its' components did (see Appendix for questions).[1] These interviews were audiotaped, transcribed, and analyzed to answer two questions:

1. What did students understand about the respiratory system in terms of structure, function, and behavior?
2. Did this understanding change as a consequence of their design experience?

Our coding scheme was based on SBF models (Chandrasekaran & Josephson, 1996; Chi et al., 1994; Goel & Chandrasekaran, 1989). We examined student interviews for evidence that they could identify particular structures and their associated functions and behaviors. We also looked for relations between structures and any properties of respiratory system components they mentioned. Table 4 presents an example of the coding criteria for the alveoli. Protocols were coded both for correct instances of each of these three categories as well as incorrect instances. Because of student absences, 18 of the 20 students interviewed were used for this analysis. An independent rater coded three protocols with 91% interrater agreement.

Because structures are most perceptually salient (and often how novices represent knowledge; Chi et al., 1981), we predicted that these would be mentioned most frequently. Second, we expected to see functions mentioned because function was so central a subject of discussion during class. We expected the children to mention least of all the causal behaviors. This understanding is more difficult to achieve because, as we noted earlier, it happens at an invisible level and involved understanding dynamic relations, and their discussions and experiences with the lungs did not reach that far. We did, however, expect that they would mention more connections between structures (relations), representing a beginning understanding that components of the respiratory system work together to achieve their function. As predicted, the students were most likely to mention structures, $F(1,$

[1]We interviewed both comparison students and Learning by Design students. Unfortunately, the recordings of the comparison students were not audible, and we were unable to transcribe and analyze them.

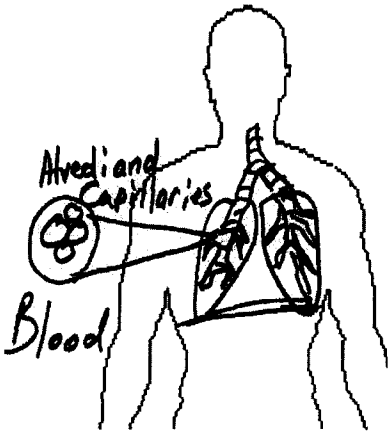

FIGURE 4 Diagram for Learning by Design student E at pretest.

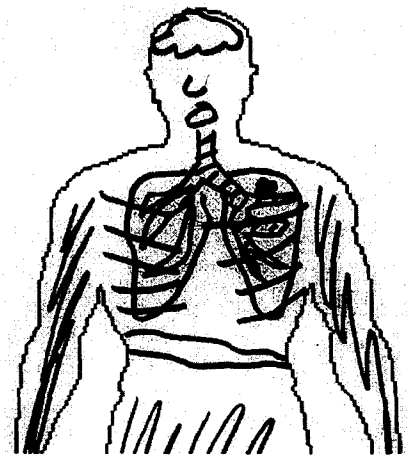

FIGURE 5 Diagram for Learning by Design student E at posttest.

17) = 505.00, $p < .001$; see Table 5. They were next most likely to mention functions, followed by behaviors, $F(1, 17) = 197.4, p < .001$; $F(1, 17) = 11.02, p < .005$.

The students had a small but significant increase in the number of structures they included at post interview, $F(1, 17) = 6.25, p < .05$. It is notable that the students most often included the brain or blood vessels after instruction, suggesting they took a more systemic view as they considered parts of the body that had less direct links to respiration. The number of behaviors mentioned increased as well,

TABLE 4
Example Coding Criteria for Structure "Alveoli"

Structure	*Alveoli*
Relations	Component-of lungs, works-with capillaries
Behavior	Gas passes from high concentration to low across semipermeable membrane
Properties	Elastic, semipermeable
Function	Gas exchange

TABLE 5
Structure-Behavior-Function Results

Category	*Pre*	*Post*
Structures*	7.00 (1.61)	7.61 (1.20)
Relations*	0.33 (0.69)	1.17 (1.20)
Behaviors*	0.94 (0.99)	1.80 (1.30)
Properties	0.44 (.62)	0.72 (0.75)
Functions	5.17 (1.25)	5.22 (1.52)

*$p < .05$.

$F(1, 17) = 5.78, p < .05$, due to an increase in the number of both incorrect and correct behaviors. Students' understanding also became more coherent, as shown by an increase in the number of relations they mentioned, $F(1, 17) = 6.16, p < .05$. These results indicate that they were thinking more about how the system worked and the relations among the components.

We can see this early emphasis on structures in E's pretest interview:

I: What's involved in breathing?
E: Your lungs
I: Anything else?
E: Oxygen gets there from the body ... .

She knew that the lungs were involved and that they had something to do with transporting oxygen. When she explained how the diaphragm worked, her ideas were related to it being a structure that physically blocked the transmission of disease saying, "Like if there is a disease, the diaphragm blocks the way of the disease going into the lungs." After this unit, E (and many of the LBD students) had an expanded understanding of the relations between structures and she placed a greater emphasis on the function and behavior. In particular, E's responses to the interview indicated that she was considering the role of the muscles in breathing and how gas exchange occurs:

I: Could you tell me what you know about breathing?
E: Well, your diaphragm goes down and your rib goes out and it just causes you to breathe.
I: Anything else?
E: Do you mean like oxygen and all? The alveoli and the gases tend to lower concentration because they don't want to be pushed so they go the capillaries.

We do not suggest that this is a complete understanding, but it is quite different from where she began. She had constructed a rudimentary understanding of the mechanics of breathing and diffusion. The student seemed to have better functional understanding of the system components, although it is not clear that she had a globally coherent view. She was on her way, but as Linn (1995) suggested, she still needed additional support to integrate multiple levels of understanding.

DISCUSSION

In several respects, this trial was a great success. The children were enthusiastically engaged and were beginning to understand the respiratory system as a system. Students learned about as much as could be expected based on predictions made by Linn (1995) and Schauble et al. (1991) and based on our own predictions. Their design activities seemed to promote thinking about the internal workings of the respiratory system. The LBD students had a better understanding of lungs and the respiratory system than did students in the comparison class, and their grasp of connections between parts was better (i.e., they were thinking of the lungs as part of a system) after instruction than before. Even given the severe time constraints and relatively crude experiments and materials, students improved their mental models of respiration. We are encouraged by models students constructed, their responses to the interview questions, and the in-class discussions they had after completing their projects. Even without the implementation being "perfect," the students learned more than in a more traditional classroom and were on their way to developing an understanding of the respiratory system as a system.

On the other hand, we realize now that we did not give enough priority, in our classroom implementation, to the kinds of activities that explicitly support systematic thinking about systems and models. Aiming toward the construction of working models of some piece of an artificial or real lung, we think, would have promoted better understanding of causal behavior. Making available to students the kinds of materials needed to build working devices would have helped. Had students tried to design something that worked earlier, they might have been able to engage in much more focused investigation. Had we introduced them explicitly to the language of structure, function, and behavior, perhaps they would have begun thinking about

causal behavior earlier. Had they interleaved presentations and reflective discussions with iteration toward a working model, they would have had more opportunities to learn from each other, to reflect on and revise their understandings, to gain motivation to learn about causal behaviors, and to be successful at making something work. These practices, we think, are as important as those that did get enacted well in the classroom: getting students to ask questions, motivating them through a significant, engaging problem-solving activity, keeping students engaged through a learner-centered approach, involving students in self-directed investigation, helping them focus, planning, monitoring, and reflecting.

Of course, one can't think about integrating such practices into the classroom without thinking about time and without thinking about significant teacher professional development to help teachers understand how to facilitate deep learning. The amount of time allocated to a curriculum unit is limited, and managing time in the classroom is critical to enabling integration of all of these important practices. As others are recommending (e.g., Linn & Muilenberg, 1996), we see a need to allocate more time to fewer units, allowing students to dig deeply into some parts of the curriculum and spend less time on other parts. To manage the timing of design activities well, we need to understand the affordances they provide and how to best take advantage of those affordances. Design is similar to but not exactly the same as problem solving. It can have affordances for knowledge building and integration that problem solving doesn't have, but to be able to take advantage of those affordances, we found from this design experiment, we need to do a better job of constructing design challenges, we need to provide materials for construction that afford asking and answering the important questions, and we need to allocate and sequence time in different ways. Construction of working models is important, as is the opportunity for dynamic and timely feedback.

Affordances of Design

Design in the real world generally means coming up with solutions to constrained, often ill-defined, and usually open-ended problems. Engineers design devices such as airplanes, bridges, cars, and computers. Architects design buildings. Strategic planners design plans. Nutritionists design menus. Each is constrained by time, materials, cost, physics, biology, and so on. Designers work within their constraints, trading off benefits here with disadvantages there to get to solutions that make the best of what is available. They consider multiple potential solutions along the way, eventually focusing on the details of one that seems to have the best potential for success under the circumstances. In the real world, designing means not just coming up with ideas, but carrying them through to fruition. It requires doing enough analysis at the planning stage to be relatively sure that they will work, implementing them, monitoring the implementation to be sure that all is in order, and testing the product as well as possible to be sure it works.

Studies of learning show that learners need the opportunity to apply what they know and get feedback—to recognize where their conceptions might be incomplete or faulty and to generate interest (e.g., Chinn & Brewer, 1993; Collins et al., 1989; Kolodner, 1993). Designing and construction afford rich opportunities for doing just that. One designs based on one's conceptions. After building a working design and trying it out, one is confronted with the need to explain unexpected results to determine if they are problems of construction or problems of conception (Kolodner, 1997; Linn & Muilenberg, 1996; Schank, 1982, 1999). Another way to get feedback on one's conceptions is to explore a working device, or, alternatively, a computer simulation, making predictions about what will happen in certain circumstances and then observing what really happens. When one's predictions fail, one discovers that one's conceptions are faulty and one develops a need to explain.

The lung challenge afforded generating questions and coming up with ideas, but it did not afford coming up with solutions that could be tested. As discussed earlier, it was not the kind of challenge that one could bring to fruition. As a result, students had a hard time getting to a point where it made sense to grapple with the details of implementation. Yet it is in implementation that design challenges have their most powerful affordances for learning. When one can build and test a device or some piece of it, one can grapple with one's conceptions. A device that does not work signals a lack of full understanding. The best design challenges for promoting learning are those that afford construction, testing, timely and authentic feedback, and revision.

An important affordance of design challenges that was achieved in the lung challenge is making connections between the science the children are learning and its usefulness in the world around them. Helping people function better is a real world challenge that children can relate to, and it is clear to them that one needs an understanding of how the body works in order to provide that aid to people. A good design challenge will make clear the utility of learning targeted facts, concepts, and skills.

A problematic episode in the implementation of the lung challenge shows another potential affordance of design challenges, one that was not taken advantage of in this design experiment. Trying to achieve a design challenge can focus and guide investigation, yet the lung challenge was not used that way to its full advantage. Recall that the lung challenge and Mr. D's facilitation of it seemed to help students focus their investigations. But when Dr. A entered the room to help students begin design, construction, and testing, it became clear that their investigations had not been as focused as they could have been. Students had investigated to learn about the lungs and respiratory system for 4 days before they began to work on developing and building their designs. Dr. A helped the students discover that although they had listed many ideas and facts during that time, there had been no organization to their investigations; student knowledge was broad and unfocused.

She helped the students to focus, and further investigation over the next week was in the service of designing and constructing models. This lack of focus is not necessarily bad, but had those days been spent on more focused investigative activity, there might have been time available for iteration and refinement.

Because time in classrooms is always short, we propose that students begin by attempting to get something to work or examining some phenomenon significant in achieving the challenge, and then generate questions and investigate based on what that activity suggests is important (Kolodner et al., 1998). Some educators question whether students can get started without some background knowledge. Our experience is that there is always something they can get started with based on what they already know—it is important to determine what that something is. For example, in a parachute challenge (Holbrook & Kolodner, 2000), we have students "mess about" with coffee filters—they spend 20 min simply trying different ways of taping filters together, making holes in them, stacking them, and so on, to see what seems to make a difference in influencing their rate of fall. Their observations guide their questioning, and the questions they ask are the ones that make a difference both in understanding air resistance and in designing a working parachute. For a bridge challenge, we have students spend a half hour building their first bridge. The differences between the capabilities in the students' bridges engage students in asking questions about structures and forces. As they learn more about the answers to those questions, they are able to design and then build better and better bridges based on their accumulated knowledge. For the lung challenge, we might have had students begin by "messing about" with the spirometers, noticing the differences in their breathing capacities in several conditions, relating that back to the challenge, and generating questions based on that experience. Alternatively, we might have given them simple pumps and had them "mess about" with them to notice what affects their performance. Using such a tactic in other units we've designed (Kolodner et al., 1998), we have been able to get students to focus their investigative activities and connect science to construction much earlier in the sequence of activities. In addition, messing about helps students connect what they already know to the demands of achieving the challenge.

Choosing the Right Construction Materials

In addition to achieving focused investigation during a design challenge, it is important that the materials students "mess about" with and construct with have affordances and constraints that promote identification of the full range of important issues. The balloons and straws and plastic bottles we made available provided affordances for getting things in and out of something by blowing or pumping air. But we provided no materials that could be used for filtering, and we provided no materials that could be used to build a working pump. It should be no surprise, then,

that most students focused on getting air into and out of the lungs and only one team considered issues of gas exchange. It should be no surprise, either, that only one team recognized a need to investigate issues associated with controlling the flow of air into and out of the lungs—the team that brought an electronic construction kit from home and built a working pump.

Were we to redo this episode, we would do two things differently with respect to materials:

1. We would provide students with materials that allow filtering (e.g., fabrics with different size weaves, colored water) and had at least some of them "mess about" with those materials early on. This might have led students to recognize the need to focus on gas exchange in their lung models, and it might have led them to ask questions about gas exchange and identify a need to design and conduct experiments looking at how differences among materials result in differences in movement of molecules. They could have compared diffusion through fabrics with different size weaves, foil or plastic wrap with different size holes, crumpled up fabrics versus tightly stretched ones, and so on. Such materials and experiences would have provided students with visible and dynamic feedback about the relation between properties of materials and their affordances for gas exchange. It is quite easy with such materials to see what happens and to compare predictions to reality.
2. We would have made available materials that would have allowed children to design, construct, and test working pumps. Some children, for example, brought electronic construction kits from home and implemented working pumps with those. Those who could build working models of pumps experienced the differences in pump action when more or less force was brought to bear. Experiencing that, they recognized that they would have to control the pump in an artificial lung so that it worked at the right speed and force for the rest of the body. Those who had no experience with the working pump didn't have the kinds of experiences that suggested they think about this issue.

Materials provided to students for messing about and construction can focus investigation through their affordances or poorly constrain what students think about through their lack of affordances. It is important to consider the range of issues we want students to investigate as part of a design experience, to choose materials that will afford identification of those issues and their productive investigation, and to give students experience messing about with those materials early on.

Connecting Modeling and Design

Of course, even with the best of materials, not all design challenges will have all of the affordances listed earlier. As we see with the lung challenge, some challenges

that can make excellent connections between science and the world fail to afford timely construction, feedback, and revision. Not every design challenge that can motivate a need to learn is achievable in a classroom. Indeed, engineers and scientists use modeling as an investigative strategy to study precisely those phenomena that are not easily perceivable, timely, or of the right scale.

This suggests a natural connection between design and modeling. The design challenge can be used to promote engagement, questioning, and connection to the world. It can then help students recognize that to learn what's needed to achieve the design challenge, they can use an investigative method engineers and scientists use—modeling.

We have learned, however, both through the design experiment described here and in other LBD classes across a variety of sciences (e.g., when modeling the erosion of coastal islands [earth science] and when designing a propulsion system [physical science]), that students and teachers need help to understand models and their function. We've come to realize that if we expect students to model some phenomenon, we must include, as part of our classroom activities, a discussion of what a model is, what we can use them for, and what kind of fidelity is needed for a model to be useful; in addition, we must help students move iteratively toward the design of better and better models, helping them see that models with more fidelity help them learn more.

Applying this suggestion to the lung problem, we would have helped the students identify the phenomena they needed to understand to design an artificial lung, then introduced modeling to them as a method for studying some of those phenomena, then helped them to design and build models (all addressing the same phenomena or each addressing different ones), iteratively redesigning the models until they reached an appropriate scale and fidelity, then helped them use those models to learn the ins and outs of the phenomena they were investigating, brought them all back together to show each other what they had learned, and then returned them to the design challenge, applying what they had learned in thinking about its solution.

Design can serve modeling as well. Model building and model running are becoming increasingly used in science classrooms, but not every model-building activity that one could do in the classroom will necessarily sustain sufficient engagement to support deep learning. A design challenge is one way of providing a reason for engaging in modeling.

Getting to a Systems Understanding

The earlier discussion has made several suggestions about effective design challenges. Good design challenges for learning: (a) afford construction, testing, timely and authentic feedback, and revision of something that works; (b) make clear the

utility of learning targeted facts, concepts, and skills; (c) focus investigation at a concrete level; (d) can serve as vehicles for promoting model design, model building, model running, and an understanding of modeling as an investigative method; (e) should be supported with materials that promote the construction of working models; and (f) can be orchestrated such that students will understand the relation between the challenge and any model building and testing activities they are doing.

But more is needed than simply building and refining working models to get to an understanding of systems. We believe that if the conceptual framework and vocabulary of systems (structure, function, behavior) had been integrated into the children's discourse, they might have moved more quickly into a systems understanding. In particular, it would have given them tools for transferring what they saw in the resources to achievement of the design challenge. For example, students spent a lot of effort trying to understand how the diaphragm acted as a pump. They were fascinated with a CD-ROM that had many animated examples of different kinds of pumps. They spent a lot of time examining the pressure regulators that are used for scuba diving and a manual bellows that might be used to fan a fire. Helping them understand those as systems with working parts that have certain ways of behaving and that carry out functions might have helped them to better understand the respiratory system as a system.

Through this case and through our experiences in earth science and physical sciences classes (Gertzman & Kolodner, 1996; Kolodner et al., 1998), we have learned that to promote understanding of working models and complex systems, students need help to break problems down into functional subsystems. They need to build working models of subsystems, put some of those subsystems together, and focus on the interactions between the functional subparts.

PUTTING IT ALL TOGETHER: FACILITATING LEARNING IN THE DESIGN CLASSROOM

Taking into account the full range of lessons we extracted from the lung episode, we recommend the following sequencing of activities for good learning from design activities:

1. Presentation of the design challenge with appropriate material to promote engagement.
2. Engagement in some quick construction activity or an activity that has students investigating how some artifacts work to get students started recognizing specific issues they need to address to achieve the challenge (what we referred to as "messing about" earlier). It is important here that the materials they have available and the guidance students have for messing about be chosen such that students are able to identify a wide range of the issues that need to be addressed.

3. Whiteboarding or some other reflective and planning activity that gets students together as a class to record ideas, learning issues, and plans.

4. Planning and carrying out some of the investigations that will help them address some significant subset of the issues they have identified as important (e.g., through reading, experimentation, modeling), along with presentation of findings to the class, discussions of the applicability and implications of findings, and return to the whiteboards to articulate what they have learned and how far they have come; it is entirely appropriate here to have different groups in the class investigate different topics.

5. Revisiting the design challenge to apply their new knowledge, planning their best solutions based on what they've learned so far, and presenting them to the class.

6. Iterations of construction and testing of solutions interleaved with additional investigation as needed and with presenting to each other what they have done and learned with each iteration of their designs.

7. Final presentations, reflection, and review.

We suggest that students report on and share the results of investigations, their design ideas, and their testing experiences with each other. This provides a venue for individuals to become cognizant of issues and explanations they might not have considered themselves and a venue for science talk in the context of a need to explain design ideas. Each presentation should have several components: (a) presentations by students to each other, with the expectation that students will make clear the science content they are learning or applying; (b) identification of misconceptions or holes in student knowledge; and (c) discussions and activities aimed at addressing the essential issues that arise, whether they are issues the children recognize or shortfalls the teacher recognizes (e.g., children's lack of understanding of what a model is). Presentations should be made to the class, with class members in the audience taking an active role in advising their peers. Indeed, this is the sequencing that the LBD group is using in the newer challenges we are authoring (e.g., Kolodner et al., 1998).

There are several challenges, however, to making such an approach work. First, it is important to recognize that this cycling needs time. We could not have done all this in 2 weeks of the lung challenge. Doubling that time would have been more appropriate. Second, it is important to recognize that there are many activities within this cycle that are not familiar to students or teachers. The teachers we've been working with prefer to introduce students to design and modeling practices early in the school year in a way that doesn't require deep learning of science content at the same time (Holbrook & Kolodner, 2000; Kolodner et al., 1998). This minimal proficiency with design and modeling practices allows students to use and refine those practices over time and in the context of focusing on learning content rather than having to learn practices and content at the same time.

The biggest challenge, perhaps, is in helping teachers becoming comfortable with a sequence of activities like what was suggested earlier. Two traditions in science education made this difficult for us to promote in Mr. D's classroom and make it difficult, in general, for traditionally trained teachers to take on a design approach. First, it is the tradition of science teaching that one does not begin to "do" until one has investigated sufficiently to know what one is doing. Second, the tradition in education is that each investigation or activity in a classroom ends in a single final product. When applying these principles in the LBD classroom, we see significant up-front time being spent on investigating, and we see teachers end the unit after students have finished constructing their first model. Too much investigative time too early results in too little time left later for iterative design and construction. We've seen this happen across the classrooms of many excellent teachers we've worked with and across the science disciplines, even after extensive teacher development. Experiences with PBL suggest that one's early understanding of a posed challenge can focus investigation in ways that make the investigation more fruitful (Barrows, 1988; Barrows & Kelson, 1995). More recent LBD experiences show that one does not need to sacrifice investigation to iterative design (and feedback) if students begin their designing early (before investigation), using those early "quick and dirty" design activities to help them identify what they need to investigate (and why), and then interleave investigation with construction and testing (e.g., Kolodner et al., 1998).

Even with these assurances, though, we find that teachers who are comfortable with scaffolding question asking, investigation, and the construction of initial conceptions take a long time to become comfortable with managing design discussions, explicitly planning one's designs, explanations of what doesn't work, and iteration and refinement of products and conceptions. The tradition of doing something once and being finished makes teachers worry about the material becoming redundant and uninteresting to the students if they "repeat" it. Their lack of experience with designing and modeling makes it difficult for them to feel comfortable staying with an activity for several iterations, to completely grasp design's affordances, and to articulate to the children the reasons for what they are doing. Their own lack of deep understanding about how things work and about the science they are teaching makes it difficult for some to scaffold explanation of why devices aren't working and to help students understand more deeply.

When we aren't comfortable with a new practice, we often fall back on what we are comfortable with; this is exactly what we saw Mr. D doing. When he joined us, he was already an excellent facilitator of collaboration and an excellent scaffolder of inquiry. He didn't know the content well, but he was comfortable learning along with the students. He learned from us, during a summer workshop, about design activities and how to promote learning from project- and problem-based activities. His enactment in the classroom is typical of what we see in the gifted teachers we are working with who buy into and understand the goals of LBD. They feel good

that we are telling them that some of the nontraditional skills they are already good at are important (e.g., facilitation, scaffolding, managing collaboration), and they work hard to emphasize those in their enactments. Their lack of comfort with the new practices we are helping them learn, however, may cause them to avoid those practices or be slow to add them to their repertoires.

A challenge for our initiative and for other innovative curricula is to help teachers master those new skills well enough before going into the classroom that they are willing to give them a try. In our recent teacher workshops, we give teachers the opportunity to practice those new skills with middle schoolers who are part of a science summer camp. Many of them do enact the new skills more comfortably in the classroom as a result. But many still need additional coaching after they enter the classroom. A major challenge, if we want to promote a design approach more widely, is to find better ways to help teachers grow and learn. We need to find ways to help teachers learn the affordances of design for science learning, to help them learn and use new practices, and to help them learn science topics and science process skills more deeply. We need to find ways of helping teachers learn that will allow them, like their students, to have the time they need to deeply learn new practices and content and to learn in an environment where they can help each other grow.

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APPENDIX

Interview questions

1. How do you breathe? After children responded, they were always prompted "What else can you think of?"
2. What do the lungs do?
3. What are some important properties of lungs that make breathing possible? "What is it about the way the lungs are made that makes breathing possible?"
4. Draw a picture of the parts of your body involved in breathing (Children were given an outline of human body and asked for an explanation of what they were drawing if it was not obvious).
5. What is respiration? Why do we need oxygen?
6. What do we mean when we talk about the respiratory system? If children mention several parts, ask "How do those parts work together?"
7. For each of the terms that I am going to mention, tell me how that is related to breathing: (a) ribs, (b) muscles in chest, (c) diaphragm (if student does not know what this means, you can tell them that it is a muscle and point to where the diaphragm is located), (d) brain, (e) alveoli (or air sacs), (f) red blood cells, (g) carbon dioxide, (h) oxygen.
8. How would you expect the lungs of an elephant to be different from the lungs of a human being? Why?
9. How would you expect the gills of a fish to differ from the human lung? Why?
10. Emphysema is a disease that damages the alveoli. How would this affect a person's ability to breathe? Why? How would that affect the lungs' ability to get oxygen into the body and remove carbon dioxide?
11. Muscular dystrophy is a disease that weakens muscles. How would this affect a person's ability to breathe? Why?
12. In pneumonia, the lungs fill with fluid. How would this affect a person's ability to breathe?

TRUE–FALSE TEST

____1. The air we breathe goes through the windpipe on the way to the lungs.
____2. The ribs and the muscles pull air into the lungs when you take a breath.
____3. The cells of the body use oxygen as a fuel.
____4. During exercise, we breathe faster.

____5. During breathing, oxygen moves from the blood into the lungs.
____6. When we are asleep, we breathe faster.
____7. The lungs push the ribs and the muscles out when you take a breath.
____8. The red blood cells turn oxygen into carbon dioxide.
____9. When we sleep, we use less oxygen than when we are awake.
____10. During exercise, we use more oxygen than we do at rest.
____11. During breathing, carbon dioxide moves from the blood into the lungs.
____12. The cells of the body produce carbon dioxide as a waste product.