Title

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Designing for Understanding: Children's Lung Models

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Abstract

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 (SBF) relationships to understand as well. Design activities, which allow exploration of the way a system works and which eventually require deep understanding of that system for success, 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 sixth grade children learned about the human respiratory system by designing and building artificial lungs. Students were interviewed pre- and post-instruction. Results of these interviews were analyzed using an SBF model for describing their understanding of the respiratory system. We consider the results in light of the children's actual activity and discuss some of the lessons learned.

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. The whole is often greater than the sum of the parts. Understanding a system involves considering the causal behavioral interactions and functional relationships between parts and with other systems. Such comprehensive understanding typifies scientific analyses of complex systems, yet is very difficult to learn (Feltovich et al., 1991). We have developed a methodology for learning about systems through design activities. We report on an (early) experiment, where children learned about the respiratory system by designing and building a subpart of an artificial lung.

Why Learn By Design

Design activities are particularly suited for helping learners understand systems because of the emphasis on functional specification. 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 functions and the principles behind accomplishing them. Designers also sequence and inter-relate multiple functions. They continually evaluate how completely functional requirements are satisfied. Because of their emphasis on function and iterative refinement, solving design problems has the potential to afford exploration of issues important to understanding science concepts.

Implementation of learning from design, however, is complex. Schauble et al. (1991) report that when children do 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. Incorporating reflective activities is important to encourage an understanding-oriented approach .

We are developing an approach to learning science based on case-based reasoning (Kolodner, 1993), cognitive apprenticeship (Collins et al., 1989), and lessons learned by others working on learning from design activities. We call our approach *Learning by Design* (LBD) (Kolodner, 1997). We are developing design problems that afford sustained thinking about science and, using Problem-based Learning's (PBL) (Barrows, 1988) facilitation methodology as a base, learning what practices are most effective at engaging middle school students in learning from design experiences (Kolodner et al., 1996).

Methods

The setting for this study was two sixth grade life science classrooms in suburban Atlanta. The LBD teacher had participated in a workshop with us to learn PBL and to design problems. He had experimented with PBL earlier, but this was his first prolonged experience doing PBL or LBD.

Participants There were 42 students in the two experimental (LBD) classes. A subset of students (n=20) was randomly selected for pre- and post- instruction interviews. A comparison classroom was from the same school. Thirteen children from the comparison class participated in the study.

Instruction Students in the comparison classroom spent two weeks learning about the respiratory system by reading their textbooks and participating in teacher-directed activities such as lectures. Students in the LBD classroom learned about the respiratory system by attempting to solve a 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.

Students worked on this project for 13 class periods over two and a half weeks. The teacher acted as a metacognitive coach, modeling the kinds of questions that the students needed to ask. He often began class by reviewing the problem statement with the students and helping them generate lists of facts (about the problem and the respiratory system), ideas about solutions, issues they needed to learn more about, and action items. He helped the students use these lists to brainstorm and reflect on their progress, particularly in the early stages. Student discussion often focused on parts they needed to include in their designs and their functions. The students knew that the lungs need to bring in oxygen and remove carbon dioxide. They also knew that when they exercise they need more oxygen and when they sleep they need less.

On the third day, students began self-directed learning based on the issues in their lists. They worked in small groups using a variety of resources. The teacher moved around the classroom to check on student progress and used questioning techniques to help them move forward, locate resources, and use computer programs. The students used a variety of computer resources, including multimedia software (e.g., *How things work*) and case libraries (Hmelo et al., 1996). On the fifth day, the students did experiments to determine the volume of air that the lungs needed to move and how that changed with exercise. As the teacher asked the students to explain the changes they observed with exercise, students inferred that because the cells needed more oxygen, they needed to breathe more when they exercised. The students were very enthusiastic about this endeavor, but it is not clear that they understood the relationship between this activity and functional components of the lungs.

Work on design projects began the next day. Students worked on their projects in small groups. During this time, an engineer came in for two days to give a benchmark lesson on design and to help the children with their designs. The students continued to generate lists as they had done earlier in the project; although these lists were used to focus on what they were thinking about that day. Students did not return to earlier lists to see what they had addressed and what they still needed to consider. They spent another week building their projects. They often realized that there were problems in the design when the teacher asked the students to explain what they were doing. Students presented their completed projects to the class and fielded questions from the teacher and other students. At the completion of the project, the students spent a class period reflecting on what they had learned.

Data Collection Data were collected to examine the students' pre- and post-instruction understandings of the respiratory system. We also observed in the classroom, examined student projects, and kept logs of day-to-day activities. Prior to instruction, the 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 et al. (1994). 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. Comparison students were asked to draw diagrams and interviewed, but due to an electronic mishap, their interviews were not available for analysis.

Results

Student Projects Most of the designs that the groups constructed were appearance-based. 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. One group of students used a motor to drive the movement of air and noted that, for their artificial lung to work correctly, they would need sensors to determine when there was enough air. When the students presented their projects, their classmates often pointed out flaws in their designs. However, the limited time available did not allow time for revision.

Conceptual Knowledge Test The children in the LBD classroom increased their scores from pre- to posttest (Pre M=8.55 sd= 2.37; Post M= 9.45 sd =1.50; F (1, 32)= 6.23 $p< .05$) whereas the comparison students did not (Pre M=8.64 sd= 1.82; Post M= 9.21 sd=1.85; F (1, 32)= 1.76 $p>.15$). These results are encouraging but are only minimally informative in understanding how the children's mental models changed. Better information comes from examining the children's drawings and their responses to clinical interviews.

Diagrams A holistic coding scheme 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.

At the lowest level was the "Lung as a bag" model. This model indicates that there are some hollow structures in the chest but there are no connections to other systems. There is no evidence that that the lungs do any processing. This is a very limited model with only some superficial structural features.

Model Two was the "It's all in the chest." In this model the students drew pictures of the lung and 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.

More sophisticated was Model Three. Here, students' drawings included connections between the different structures that they drew. It was clear that the air spaces were an integral part of the lung.

Models Four and Five are increasingly global, systemic models. They include connections to the rest of the body such as the brain and peripheral blood vessels. Model Four indicates some misconceptions, most commonly that the abdominal organs were part of the respiratory system (the children conflated the role of air, food, and blood). Model Five is the most complete and correct.

The pre- and post- test results for the LBD and comparison students are shown in Table 1. At pretest, the most common model for the LBD group was Model Two. 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. For the comparison students, Model One was the modal model. It is not clear why the LBD and comparison students differed at pretest. After instruction, the LBD students had a reliable improvement in their models (Sign Test, $p<.005$) whereas the comparison students did not ($p>.25$). Twelve of the LBD students showed more sophisticated models at posttest, and 5 showed no change (one student got worse). For the comparison class, 9 students improved and 4 had less sophisticated models at posttest. These results indicate that the LBD students constructed a better understanding of how the structures were related to each other and viewed respiration more systemically.

Table 1. Categories of Diagrams

	Comparison		LBD	
Model	Pre	Post	Pre	Post
One	8	2	3	0
Two	1	3	8	5
Three	1	7	3	8
Four	2	0	2	1
Five	1	1	2	4

SBF Analysis of Interview Protocols We further analyzed student understanding of the respiratory system using a coding scheme based on structure-behavior-function (SBF) models (Chandrasekaran et al, 1996; Chi et al., 1994; Goel et al., 1996). SBF theory posits that devices and complex systems can be specified representationally in terms of their structures, behaviors, and functions and the relationships between them.

Table 2. SBF Model of Respiratory System

Structure	Behavior	Function
Lungs	Gas passes from high concentration to low across semi-permeable membrane	Bring in oxygen, remove waste
Diaphragm	Lower pressure in chest by increasing volume	Move lungs
Brain	Send signals to respiratory system, Receive and process signals regarding body status	Control respiration

Structure refers to how a system is built, characterized by the size, shape, and materials of objects. The main respiratory system structures accessible from common experience are the superficial features: the mouth, the nose, and the throat. At the cellular level, respiratory structures include hemoglobin and cellular membranes. Our focus was on student understanding at the intermediate level of organ structures: the lungs, the diaphragm, and the heart. Behavior encompasses the dynamic elements, the mechanisms for changes in the structural state of a system. The most accessible behaviors are the visible ones, e.g., breathing. *Behavior* includes causal mechanisms, and in general, behavioral aspects of systems are least well understood (Feltovich et al., 1991), and are often not thought about until an anomaly in the normal behavior of a system arises (Murayama, 1994). *Function* is the purpose of a system, operationally defined by effects on a structure's environment. The lungs' function is to supply oxygen to the body and to remove waste. Novices in a domain typically begin to understand a system at a superficial structural level and only later begin to understand how the structures are related to each other. Experts typically represent systems at the levels of function and behavior (Chi et al., 1981). Table 2 presents our analysis of the respiratory system in SBF terms.

Transcripts of students' clinical interviews were analyzed to answer two questions:

1) Did students understand the respiratory system in terms of structure, function, and behavior?

2) Did this understanding change as a consequence of the design experience?

We first examined student interviews for evidence that students could identify particular structures and their associated functions and behaviors. Table 3 presents an example of the coding criteria for the alveoli. In addition, we coded whether the students identified relationships and properties that contributed to behavior. For example, alveoli are an integral part of the lung and are semi-permeable. Because structures are most perceptually salient (and often how knowledge is represented by novices), 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 it happens at an invisible level and involved understanding dynamic relationships.

Table 3. Example coding criteria for structure "Alveoli"

Structure	Alveoli
Relations	component-of lungs, works-with capillaries
Behavior	gas passes from high concentration to low across semi-permeable membrane
Properties	elastic, semi permeable
Function	gas exchange

We coded the protocols for two other kinds of knowledge that seem to be at the border between structure and behavior: relations and properties. Relations refer to the part-whole relationships and interactions between parts of the system. Properties are those features of the structure that afford the dynamic behaviors. Protocols were coded both for correct instances of the SBF categories as well as incorrect instances. Because of student absences, 18 of the 20 students interviewed were used for this analysis. Three protocols were coded by an independent rater, with 91% interrater agreement.

As predicted, the students were most likely to mention structures ($F(1,17)=505$; $p<.001$; see table 4 for means and standard deviations). They were next most likely to mention functions, followed by behaviors ($(F(1,17)=197.4$; $p<.001$; $(F(1,17)=11.02$; $p<.005$). Students were least likely to mention relations and properties.

The students had a small but significant increase in the number of structures that they included at posttest ($F(1,17)= 6.25$; $p<.05$). It is notable that the students most often included the brain or blood vessels after instruction. suggesting they took a more systemic view. The number of behaviors mentioned increased as well ($F(1,17)= 5.78$; $p<.05$), 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. However, they also show that students were not constructing a more correct understanding of the dynamic behaviors.

Table 4. SBF 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)	1.8 (1.30)
Properties	0.44 (.62)	0.72 (0.75)
Functions	5.17 (1.25)	5.22 (1.52)

Questions about diseases were used to examine the flexibility of students' knowledge. For each of the disease questions, the students were told something about the disease and asked how it would affect breathing, e.g., "Muscular dystrophy is a disease that weakens a person's muscles. How would that affect their breathing?" Two of the questions were related to diseases that affected the alveoli: emphysema which destroys the air sacs and pneumonia which fills them with fluid. The third question was about muscular dystrophy. For the first two questions, the key behaviors were related to diffusion; for the last question, it was related to understanding the diaphragm as a pump. Considering that the students' activity was focused on how to get the air in and out of the lungs, we expected to see change on the muscular dystrophy question but not on the others. The students were given one point for mentioning that breathing is harder (indeed, it is) without a justification. They were given another point if they invoked a cause or consequence. All other responses were scored as a zero. The frequency of one and two-point responses is show in Table 5.

A significant improvement was observed in students' responses to the muscular dystrophy question (Sign test, $p=.01$). Students also demonstrated marginally significant improvement on the emphysema question ($p<.07$) but no improvement on the pneumonia question. Although the emphysema question was designed to probe the students' understanding of the relationship between diffusion and surface area, it may have instead tapped their understanding of the relation of the alveoli to the lungs. This alternative explanation is consistent with the results of the diagram drawing and their increased understanding of relations in the system.

Table 5. Frequencies for Disease questions

Question	Points	Pre	Post
Emphysema	1	9	6
	2	8	12
Muscular Dystrophy	1	9	5
	2	6	13
Pneumonia	1	14	11
	2	2	5

Discussion

Did children's views of a complex system became deeper after an LBD experience? The answer to this question is yes and no. Students did achieve a more systemic understanding of the respiratory system. Even given the severe time constraints and relatively crude experiments and materials, students were able to improve their mental models of respiration at the molar level by thinking of the structures, behaviors, and functions of breathing. We are cautiously encouraged by students' responses to the SBF and disease questions. The design activities seemed to promote student thinking about the internal workings of the respiratory system. But their understanding was often incomplete. We believe this is due to several factors related to the way the design activity was carried out.

Defining Problems Functionally Students focused on building models that *looked like* lungs rather than ones that *worked like* lungs. Students developed a deeper and more flexible understanding of those concepts they actually dealt with. They 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. But they never really understood the pumping action of the diaphragm in terms of the underlying physics.

In retrospect, we asked students to do too much in too short a time. But more importantly, our problem description and class activities did not emphasize enough the building of *working* models. A full working model of the lung might be too much for a middle school student to do, even in a longer amount of time, but we believe this can be countered by helping students break problems down into functional subsystems, asking them to build working models of subsystems, then asking them to put some of those subsystems together, focusing on the interactions between the functional subparts.

Dynamic Feedback The Artificial Lung project helped students think about causal behaviors. However, they had no opportunity for dynamic feedback, making it difficult for them to recognize when their understandings were incorrect and in need of revision. Trial and feedback are critical to learning complex concepts (e.g., White, 1993); the shallowness of our students' learning, particularly at the cellular level, illustrates just how important such feedback is. Building and trying out working models, as suggested above, would have helped here. Another way to provide feedback opportunities would have been to give students relevant devices to explore. For example, a bellows pump might have provided an analogy to the diaphragm. Experimenting with it might have helped them understand the relationships between volume increases and pressure decreases that are in play when we breathe.

Cycles of Design, Reflection, and Revision Earlier focus on design and an incremental approach would have given the children a chance to try out ideas that might not have been good ones, see them fail, and from that, generate learning goals, revise their understanding and their designs, and try again. Two important benefits would have accrued. First, they might have made better connections between their resource use and experimentation and their designs. Second, it would have promoted analysis and reflective discussion.

Because students did not get started on their designs and have an understanding of what they needed to learn before they accessed the information resources, much of the resource-use time at the beginning of the activity was wasted. Children had fun looking through the multimedia resources and probably learned some random facts, but if they had begun their designing earlier, they could have been more focused in their resource use, and they might have gained better understanding of what they were viewing due to their understanding of why they needed to learn it. A similar argument can be made for their experimentation.

Also important, without time to design, try things out, analyze what happened, and revise, students did not have enough opportunity for the focused exploratory activity that is so important to learning. Design can be powerful for promoting learning of complex ideas and systems because it gives the opportunity to explore in a focused way and with real feedback from the world. Design without analysis and revision loses those potentials. Managing design activities to make them iterative is essential for effectiveness. When students realized their models did not work, they should have had opportunities to develop, test, and evaluate a new understanding.

Starting design earlier would have encouraged more productive reflective discussions. Our experiences show that discussing abstract ideas is difficult for children of this age, but once they have experienced something and seen concrete results, discussion becomes deeper and more generative. Children need interactions with the world to promote their engagement in discussion and analysis of what happened, focusing particularly on areas of conflicting expectations (Chinn & Brewer, 1993). Student presentations, for example, provided opportunities for other students to point out the limitations of their models, and students did this quite well. Without time to further analyze and revise, however, students did not gain the full benefit of those discussions. Such presentations made early, based on initial designs, and then made again later after revisions would helped students recognize important issues. Also, without the need to revise their models and really make them work, students had little motivation to reflect on what others were telling them.

A System of Activities The environment was not exactly what we had envisioned as Learning by Design, but its design component was substantial enough to teach us some lessons. Our intentions were that design would guide student activities, that students would engage in multiple design iterations, that students would build working models and have opportunities for dynamic feedback, that there would be more reflection integrated into the class activities, and so on. Indeed, we stressed the importance of all of these, and others, during our teacher workshops. But the teacher had many new practices and activities he was trying to manage. It was difficult for him to incorporate so many new teaching practices at once, and to keep track of what all the children were doing and the help they needed. His yeoman's effort yielded better learning than in other classes but not as much as we had hoped for. An important lesson to take away from this is the importance of incorporating the whole *system* of design and learning-related activities; a focus on design without the supporting practices and activities that allow it to play its powerful role will not accomplish what is intended.

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