

Distributed Scaffolding: Helping Students Learn in a ‘Learning by Design’ Environment

Sadhana Puntambekar
Information Media and Technology
School of Education, U-64
249 Glenbrook Road
University of Connecticut
Storrs CT 06269-2004
sadhana@uconnvm.uconn.edu

Janet L. Kolodner
EduTech Institute
Georgia Institute of Technology
250 14th Street, NW, SUITE 143
Atlanta, GA 30318
jlk@cc.gatech.edu

Abstract: In this paper, we relate our efforts at designing and implementing scaffolding that highlights and allows students to take advantage of the affordances of a Learning-by-Design classroom. We began by integrating into the classroom a paper-and-pencil tool, *design diaries* (Puntambekar, 1997), to scaffold students’ design-related activities. Our experiences with using the diaries in middle school classrooms have helped us understand that in the dynamic, complex environment of the classroom, not all of the scaffolding can be provided with any one tool. Scaffolding needs to be *distributed* across the various agents that play a role in learning (for example - the teacher, peers and software and paper and pencil tools). We found that a system of scaffolding is required which integrates the activities that students have to carry out.

1. Introduction

In recent years there has been an upsurge of interest in design activities as a means to promote science learning (e.g. Harel 1991; Kafai, 1994; Lehrer & Romberg, 1996, Baumgartner and Reiser, 1998; Kolodner, 1997). Design problems motivate students to learn science content, and as they engage in cycles of designing, evaluating, and redesigning, they confront their understanding and misunderstanding of science concepts.

In one of our Learning-by-Design (LBD) (Kolodner, 1997) units, for example, students are presented the challenge of designing a vehicle that can carry a certain load a specified distance. As they begin to try to achieve the challenge, they raise questions about motion and forces. They conduct investigations in each topical area (friction, inertia, gravity, and so on), and as they understand the answers better, they apply their understanding to achieving the design challenge, constructing and refining the designs of their vehicles several times. Their investigations allow them to explore their understanding of science, and to apply what they are learning to the design of their vehicles. Testing and evaluation of their vehicles helps students to build on this knowledge, and understand the interactions between the systems that make it work (or not). Students work in groups, and the teacher plays the role of an expert facilitator.

Learning from design activities affords rich opportunities for learning. With proper facilitation, students have the opportunity to construct and generate rich meanings (Piaget, 1954; Perkins, 1986) as they build, test, and manipulate their artifacts. In addition, the classroom affords a rich social context (Vygotsky, 1978, Bruner, 1985) to augment the cognitive affordances of design activities. Opportunities to articulate what they are learning and justify their claims arise over and over again as students work together in small groups and engage in whole-class presentations and discussions. Individual and small-group learning, whole-class discussions, note-taking in design diaries, and presentations and critiquing during gallery walks and pin-ups provide a whole host of opportunities for reflecting on, articulating, critiquing, and refining ideas. Learning in such an environment is therefore a result of both individual and social processes (Driver, Asoko, Leach, Mortimer, and Scott, 1994).

But it is difficult to align all the affordances in such a classroom so that they are well-integrated and all taken advantage of. In this paper, we relate our efforts at designing and implementing scaffolding that highlights and allows students to take advantage of the affordances of a Learning-by-Design classroom. We began by integrating into the classroom a paper-and-pencil tool, *design diaries* (Puntambekar, 1997), to scaffold students' design-related activities. Our experiences with using the diaries in middle school classrooms have helped us understand that in the dynamic, complex environment of the classroom, not all of the scaffolding can be provided with any one tool. Scaffolding needs to be *distributed* across the agents that play a role in learning (for example - the teacher, peers, software and paper and pencil tools). We found that a *system* of scaffolding is required which integrates the activities that students have to carry out.

2. Scaffolding in a Learning-by-Design Classroom

Design is a rich process, encompassing many skills and activities. Designing requires analyzing a situation to understand the problem better, identifying what needs to be learned in order to address the design challenge, gathering appropriate information, generating alternative solutions and criteria to evaluate proposed solutions, carrying out tests and evaluations, making decisions and considering trade-offs, and justifying choices. Our understanding of the cognition of learning from design activities (Kolodner, 1997) tells us that students need to go through several cycles of trial, analysis, and refinement to develop a deep understanding of science. Each cycle allows them to apply what they know about a scientific principle that they are learning, test the application, analyze the results and the conceptions that led them to their design, and refine their conceptions so as to be able to come up with a better solution. Our early implementations (Hmelo, Holton, Allen & Kolodner, 1997), however, showed us that students needed help with nearly all of these tasks.

The support provided to a student to help carry out a task, referred to as *scaffolding*, is described by Wood, Bruner, and Ross (1976) as consisting "of the adult controlling those elements of the task that are essentially beyond the learner's capacity, thus permitting him to concentrate upon and complete only those elements that are within his range of competence". Based on the Vygotskian notion of making abstract processes more visible, scaffolding can take a variety of forms. For example, a teacher or a more capable peer could help by modeling strategies and providing suggestions (as in reciprocal teaching, Brown and Palincsar, 1987). Scaffolding can also be provided in the form of prompts and questions that help students understand the processes involved in learning (Scardamalia and Bereiter, 1985; Bell and Davis, 1996; Jackson, Krajcik, Soloway, 1998).

Our first approach to scaffolding took the form of externalizing the activities (Collins, Brown and Newman, 1989) involved in designing and in learning through design, by making clear to students the range of activities that they could carry out. We showed them the steps involved in designing and the ways those steps are often sequenced, and we provided them with prompts to support them through each of the steps. Support was provided for problem understanding, gathering information, generating alternatives, and choosing between alternative solutions. Support was in the form of *design diaries*, a paper-and-pencil tool that operationalizes the process of design. Diaries have pages associated with each of the steps of designing, and each page contains prompts to help students carry out that design step. For example, during problem understanding, we prompted with: This is what I understand of the problem (Please restate the problem in your own words). During information gathering, we had other prompts: What questions do you need to ask in order to understand the problem better? Prompts for choosing between alternative solutions included questions like these: What are the criteria against which you will evaluate possible solutions? Why do you think these criteria are important?

We used the diaries to support two life science, two earth science and a set of physical science problems¹. In order to understand how students were learning, we analyzed not only student responses in the diaries, but also observed classroom interactions. Student responses in the diaries were analyzed for evidence of science learning and for understanding of the design process. The diaries indicated some interesting trends

¹ The Jekyll Island problem, has students learning about erosion by having them design and model means of combating the erosion that is threatening the island's existence. Design a lung had students design models of the breathing system. Habitat had students design a device to study difficult to reach habitats. Crash barriers, part of a unit of laws of motion, had students design crash barriers at the end of a ramp.

in students' understanding of science and design, especially in the difficulties they had in drawing connections between design and science, and in relating the design activities to each other. Further, our classroom observations helped us to understand the classroom context, and enabled us to clarify the role that the diaries and all the other agents in the classroom (teacher, peers, resources) should play in a learning by design environment.

2.1 Student Responses in Dairies

2.1.1 Understanding the Problem

Understanding the problem is an important first stage in the design process (Atman & Bursic, 1996). To clarify their understanding of the problem, students need to think about subproblems, activate prior knowledge, come up with issues to learn more about and clarify their goals and objectives. Diary prompts for this stage were designed to encourage the students to restate the problem, think about subproblems, and any questions they might have to clarify their understanding of the problem. We found that students were unable to elaborate upon what they wanted to learn. They concentrated heavily on the components of the system and were unable to relate the components and their respective functions. This is similar to findings by Rowland (1992), who found that novices engage in very little elaboration of the problem.

2.1.2 Learning Issues

In order to help students identify the learning issues they were asked to think about what they already know about the topic and what they needed to know in order to build the model. The learning issues they raised were very general. Students did not ask specific questions related to their designs. For example in the first implementation of the Jekyll island problem (1996) students raised questions such as "Can we help the environment and help eroding/ weathering at the same time?" and "How much money is it going to cost. What if it looks ugly after we finish the island?"

2.1.3 Gathering Information

Middle school students in the participating classrooms were not used to the kind of self-directed information gathering and research that solving hard problems required. We found that they needed help with extracting useful information from the text. Most often, they copied paragraphs verbatim rather than summarizing the content. Students conducted research in an unsystematic manner and concentrated heavily on finding interesting facts. This fact finding was often, serendipitous and not related to the purpose that their designs were to fulfill. Students were unable to focus their research on the issues that they raised earlier. They were not able to link their research to the learning issues they raised and it seemed essential that students should be given more direct support for monitoring their learning.

2.1.4 Generating Alternatives and Choosing a Solution

This phase of the learning is by far the most difficult and requires complex skills. There are three activities that are required in this phase. First, students need to generate criteria that they will use to evaluate potential solutions. Second, students need to come up with two or three possible solutions and weigh them with respect to the criteria that they generated. They then need to select the optimal solution. This requires a deep understanding of the scientific concepts that they have learned, and also an ability to apply the criteria to the solutions and make a decision about each of the solutions.

We found that students understood the concept of generating criteria quite well. However the criteria that they came up with were very general. For example in the first implementation of the Jekyll Island problem, most students evaluated their solutions against criteria such as 'Cost', 'Effect on environment', 'How will it look'. Very few students came up with criteria that were related to the science concepts that they were learning, such as slowing down wave currents.

Students often got fixated in the first solution idea that they thought of and did not come up with many alternative solutions.

2.1.5 Reasoning about Devices

While going through journal entries, it was clear that students' responses in each of the stages could be further categorized to reflect their reasoning about the models that they were designing. We used the SBF (Structure-Behavior-Function) model of device representation as a guide for our coding. The SBF model (based on a model by Goel, Garza, Grue, Murdock & Recker, 1996) explains design of physical devices in terms of their Structure (the component parts), Function (the functions of the parts) and Behavior (which refers to the causal relationships between the functions of the various components of the system resulting in an action).

We found that students concentrated heavily on the components (Structure) of the design that they were working on. For example, the learning issues and the criteria that they came up with reflected their understanding of the parts of the breathing system or aspects of erosion that they were studying. As they did not focus on the function/s that their designs were supposed to fulfill, their design decisions did not show a deep understanding of science issues. Students found it especially difficult to make connections between the parts and their functions and to understand how the parts work together to achieve the necessary function/s. For example, in the lung study, very few students understood the mechanism that makes breathing possible. Their diary entries focused on the 'inhale-exhale action' but not the *mechanism* that makes it possible. This fact was also evident when students demonstrated their models. They showed the lungs expanding and contracting, and blew air into their models through the tubes. Many of their models did not show the diaphragm at all, and if it did, it was not in any way shown as being a functional part of the system. Students could not integrate science into the design process and use the design activities to 'steer' their learning of important and often difficult science concepts.

2.1.6 Links between and within Phases

Some of the students explicitly linked their research and learning to what they wanted to model. For example in the lung study, they were able to reason about the mechanism of the breathing system and understood the causal links between the diaphragm and the lungs. However, not only were many of the students unable to relate their design activities to the science that they were learning, they also could not understand the links between the various activities that they undertook. Students seemed to perceive the process as being linear and did not often see the cross links between the activities. They concentrated on single moves (Chrisiaans and Dorst, 1992) and worked on solving parts of the problem without consideration for the whole.

2.2 Classroom Observations

Our classroom observations showed us how the diaries were used in the classroom. We found that the diaries had to be better integrated with the other activities that took place during learning by design, such as building, presenting and research.

2.2.1 Need for Follow-up on Diaries

In almost all instances, students used the diaries as homework, to think about what they would do the next day. However, there was no follow-up on the work that they did in the diaries. Typically, students would complete diary pages at home and work on their models in class. As there was no follow-up on their work in the diaries, many of the interesting issues that they addressed in their diaries, and also their misunderstandings about the science issues, were left undiscussed. For example, in the lung study, students raised many interesting issues about the 'Alveoli' and the 'diaphragm' and indicated that they needed to

understand these more deeply. However, since these were not addressed, their presentations at the end of the problem showed that they still had misconceptions regarding these.

2.2.2 Insufficient Time for Reflection

Many of the students updated their designs by trial and error and did not really reason about why the changes they made to their designs, or the design features that they selected resulted in the performance they observed. For example, in an implementation in which students built crash barriers at the base of a ramp and ran cars to study the science concepts of motion, students changed features of their designs to get the desired results. However, when they were asked why their designs worked (or did not), they were unable to provide scientific explanations.

Our observations revealed that there was no time allocated for whole class discussions to talk about students' experiences. Reflection on what was learned either during building / testing or during research was not something that was typical of the classrooms that we were in. Also, once students became engrossed in the building, it was very difficult to pull them together to step back and reflect on their design. As such, there was very little sharing of ideas and experiences.

The presentations that students made after completing their designs also supported the need for justifications during the process. First, in the 'habitat' problem (where students were required to design a device for hard to study habitats), most of the students designed some kind of a camera to study the habitat. Their justifications were not very elaborate and did not specifically mention why a 'snakecam' or a 'scorpioncam' would be appropriate for that habitat. In the lung study, students did not really understand the function of the diaphragm and the mechanism that makes breathing possible. This was not revealed until they presented their models. Thus the observations helped us understand that the work that students do as individuals needed to be integrated better with their small group and whole class activities.

3. Lessons Learned

Our analysis of student responses in the diaries and classroom observations have helped us understand two main aspects of scaffolding Learning by Design. First, we now understand which aspects of the design process students have difficulty with. Second, and equally important, our analysis allowed us to identify some of the scaffolding teachers need to provide in order for the support provided by the tools to be effective.

Analysis of diary entries has helped us understand aspects of the design process that we need to support better. We found that the prompts need to be more specific. Moreover, it was clear that the support should integrate the science and the design activities in such a way that students carried out the design related activities in the pursuit of science knowledge. We have identified three levels of scaffolding - a *macro* level (the main phases), a *micro* level (the activities within each phase) and a *metacognitive* level (links between and within phases).

Classroom observations helped us understand that students need to be given more opportunities for justifying and sharing their design decisions. In order for deep science learning to happen, students have to be able to justify why their solutions fulfill a purpose, why the criteria they chose are important for their designs, what features of their models contribute to the results that they obtain, etc. We found that there should be more time allocated for whole-class discussions where the teacher plays the role of making public, what the students have observed individually or in small groups (Tabak and Reiser, 1997).

In an LBD classroom, learning occurs at many levels. Students work alone in their diaries or gather information on their own. They work in small groups during formulating their solution ideas, and when they build and test their models. They present their models to the whole class. We found that these levels needed to be seamlessly integrated in order for deep science learning to happen.

Another important aspect of the LBD classroom is that students spend a large portion of their time on building their models. It is important that they see the links between testing their models and the science concepts that are involved in making their models work (or not work). In other word their 'doing' and their 'thinking' about the models they are building needs to be integrated. Very often, it becomes difficult to interrupt their 'hands-on' activities unless sufficient time is allocated for discussions. Time for reflection and whole class discussions frequently during the unit needs to be built into the units. Reflection needs to be at the individual, small group and whole class levels.

4. Distributing Scaffolding

Our observations described above have helped us understand that there are many levels of scaffolding in the learning by design environment. First, within the design process itself, we see three levels of scaffolding (as described earlier) that can support students better. Second, not all of the scaffolding can be provided by the diaries. Teacher and peer interactions are an integral part of the scaffolding. We now have a better understanding of the kinds of activities that need to occur in the classroom. The interactions between the teacher and the students, as well as the interactions between the students as they are working *extend* the scaffolding that is provided by the tools. Scaffolding thus, is *distributed* across the tools and the context in which learning occurs, in this case classroom.

	Which process is supported	When is the tool used	How does the tool support the process
Diaries	Activities in the design process, macro, micro and meta levels	Individuals, as homework or during reflection time	Prompts and examples to support the activities
Pin-up sessions	Justifications for solution ideas, Criteria	During pin-up sessions and presentations	Teacher and peer questions
Electronic discussions	To share solution ideas, ask questions across classes and schools	After coming up with possible solutions	Peer questions
Presentations	End of the problem	Extend and generalize science understanding	Teacher, peer and expert questions

Table 1: Distributing scaffolding across agents

As summarized in table 1, scaffolding needs to be distributed across the agents in the learning by design environment. The diaries provide support to students as they are working on design activities. They help them in understanding aspects of the design process and in making connections between the activities. We have introduced ‘pin-up’ sessions in which students display their early solution ideas in the classroom. The teacher and their peers question students about their ideas and about the science content, thus making them think hard about relating their designs to the science they are learning. We have also introduced an electronic discussion tool to help students collaborate asynchronously across classrooms. We found in a recent implementation that using the electronic discussion area led to more justifications and a greater emphasis on function (Puntambekar, Nagel, Hübscher, Guzdial and Kolodner, 1997). We are also encouraging teachers to have more whole class discussions to help students reflect on their activities and to make connections between building their models and reasoning about the performance of their models.

5. Conclusion

In this paper we have discussed the findings from the LBD approach to teach science to middle school children. We have found that in an LBD environment, scaffolding is provided by many agents. In order to help students learn effectively from design activities, scaffolding needs to be distributed across the many agents. Our recent implementations have moved in that direction. We now have a new version of the diaries with a more fine-grained set of prompts. We have also introduced more opportunities for sharing and reflection in the classroom.

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