Medium-Based Design: Supporting Bricoleur Designers

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Abstract: The design of learning environments is a fundamental part of education research today. In this article, we put forth a design method, medium-based design (MBD), to create such systems. MBD is a well-formed method grounded in theory that offers designers an alternative approach to designing learning environments. This method is described by analyzing the design of two learning systems—AudioExplorer and DigiQuilt, in terms of MBD.

Keywords: design, medium-based design, educational technology, design of learning systems

Introduction

The design of learning systems is fundamental to the problems and possible solutions of education research today. Educational theory informs us that open-ended, learner-centered, constructivist systems have the potential to allow for greater learner motivation and depth of learning (Dewey, 1938, Vygotsky, 1978). Educational technology theory informs us that computing offers unique possibilities for achieving that goal by providing environments with strong personal and epistemological connections (Resnick et al., 1996). Design methods will be necessary to realize these educational potentials in everyday usage. In this article, we begin by describing the design of learning environments in general. We continue by putting forth a design method, medium-based design (MBD), to create such systems. We describe the development process of two learning environments, AudioExplorer and DigiQuilt, using this method. Both of these learning environments are examples of constructivist learning environments whose design process is quite different than previously articulated design methodologies. Understanding this design process will significantly contribute to the field of designing constructivist environments.

We do not believe that MBD is a completely new approach to designing learning environments. Rather, we believe that designers have intuitively used similar methods, and that, by describing details of medium-based design and providing guidelines that follow this approach, we are showing support and value for this approach. We argue that MBD is significantly different from other methodologies, such as goal-based scenarios (Schank et al., 1994), cognitive tutors (Anderson et al., 1995), design experiments (Brown, 1992), and the TILT model of learner-centered design (Soloway et al., 1994). While it is true that not all approaches to design are equally successful, other design methods have concentrated on a top-down approach, neglecting the *bricoleur* designer. The bricoleur style of design is different from but not worse than other approaches (Turkle and Papert, 1991). Our method, MBD, is a well-formed method grounded in theory that offers designers an alternative approach to designing learning environments. The products of varying design methods may differ from each other, and there is reason to believe that products of MBD may be desirable. Describing the important decisions that went into the design of these environments should help us illustrate how the design process and the designed products of MBD differ from those of other design methodologies. We complete this article with a discussion that begins to characterize environments designed using MBD and describes possible future research.

Designing Learning Systems

> A theory of instruction, in short, is concerned with how what one wishes to teach can best be learned, with improving rather than describing learning. —Jerome Bruner (1996, p. 40)

Designing systems that foster significant inquiry, enable meaningful artifact construction, and encourage useful interaction is fundamental to the field of learning sciences. In education, these types of environments have a substantial history going back to Fröbel's gifts and Montessori's prepared environment. More recently, these environments have been championed by educational theorists (Bruner, 1966, Zucchermaglio, 1993) and educational technologists (Papert, 1993, diSessa, 2000), under classifications such as microworlds (Papert, 1987), construction kits (Resnick et al., 1996), media creation tools (Kay and Goldberg, 1977), and inquiry tools.

If we value these constructivist environments and the models of learning they support, then learning sciences cannot simply be an observational science—one that simply observes, describes, and models the results of systems in action. While some areas of research, such as cognitive modeling (Bereiter and Scardamalia, 1987) and understanding collaborative activity (Roschelle, 1996, Rogoff, 1994), may appear to be independent of design, they are not. First, without a useful / usable system of learning, good research in these areas may not be possible. Studying how people learn is inseparable from the environment and context in which they are interacting (Lave and Wenger, 1991). Studying something without understanding design is akin to the famous anecdote about blind men trying to determine the nature of an elephant by feeling a single body part. Depending on exactly which experiment is considered, different conclusions will be reached. Second, the observational research would be far less important if designers were unable to use the research findings to inform their designs. For example, having a cognitive model for a domain is unable to help learning unless it informs the design of systems addressing that domain.

Learning sciences needs to be what Norman calls a “design science” (Norman, 1988) and what Simon calls a “science of the artificial” (Simon, 1998). It needs to create useful designs to understand how people learn and further enable that process (Brown, 1992). As such, a core goal of learning sciences research is designing such systems. Yet, there is very little work in this area that has been studied in a scientific manner. Most of the work falls into descriptions of or theories about the product, rather than about the process of creating that product. As one example, Resnick, Bruckman, and Martin (1996) theorize that what makes for a good construction kit is for the environment to have strong personal and epistemological connections. While we agree with their position, it is not clear how to arrive at construction kits that meet these goals. It is akin to being given the exact position of a maze's exit. It might help you find your way to that goal a bit easier as you know what you are aiming for, but it does not describe the path you need to follow to achieve that goal. Even more than finding the solution to a maze, design is one of the most complex of human problem-solving tasks and is far from arbitrary (Goel and Pirolli, 1992). Designers must be aware of user needs (Norman, 1988) and learner needs (Soloway et. al., 1994) and create a learning system that will meet those needs. To investigate design, ways of mapping the design space and design methods for creating useful designs are necessary.

In this paper, we define design as a process of reflection-in-action (Schön, 1987). Design is not, to use an analogy, simply following a recipe. For a great cook, cooking is not about a teaspoon of salt and a pinch of cumin. Instead, it is an active process of taking action (putting some salt in the soup), reflecting on that action (tasting the soup), locally evaluating the next step to take (perhaps a pinch of cumin), and continuing the reflection-in-action cycle. Design is not something to be done from a distance; it demands getting your hands dirty: trying things out, taking a small step in one direction, evaluating where you are, perhaps backtracking, moving on, etc. In the complex domain of learning, this is even more the case.

In addition, we define design as a process of problem solving in multiple search spaces (Klahr, 2000). Designers engage in reflection-in-action in a local point in a search space. At times, the reflection-in-action there will have exhausted its usefulness and it will be time to move on. When this happens, it is often fruitful to switch search spaces to begin a new inquiry process in a completely different space that will inform the design in a different way (Klahr, 2000). Navigating through these design points (reflection-in-action cycles in one search space) is fundamental to good design. We define three sometimes-overlapping search spaces of *mind* (what is going on in the mind of the learner), *activity* (how do the activities the learner engages in support the learning), and *environment* (how does the environment support the learning) that designers can move through when designing learning systems. The first two search spaces, mind and activity, are already well established. Investigating how learners think and learn (what is going on in the mind) is important to informing the design of useful learning systems (Bruer, 1993). At the same time, what activities learners do is fundamental to them learning. Brown (1992) argued that design experiments offered a way for classroom and laboratory studies to be complementary. She argued that the classroom is a better setting for investigating the complex activities the learner is engaged in, whereas the laboratory is a better setting for investigating the cognitive processes of the individual learner. In the framework we are proposing, a design experiment (as Brown states it) is a design process with design points moving between the mind and activity search spaces (see Figure 1). To those two, we add the environment search space, that we feel has been neglected. It is clear that this search space has been acknowledged before. For instance, both Montessori and Fröbel highly valued the affordances that the right environment can have for learning.

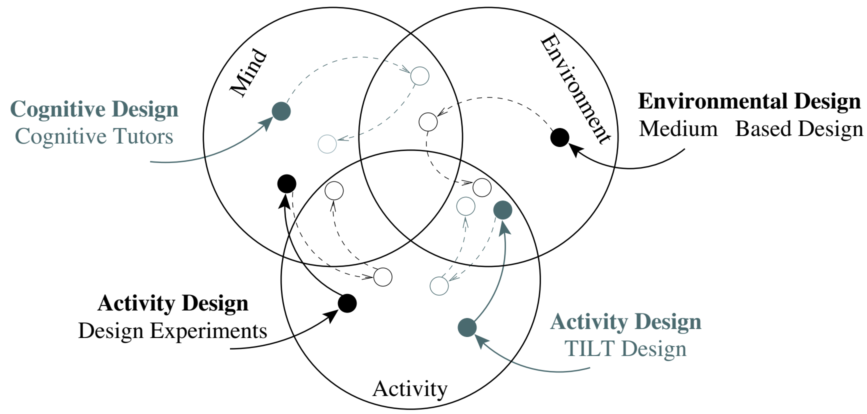


Figure 1: Mind, Activity, and Environment Search Spaces & Analysis of Several Design Methods

Figure 1 shows the three overlapping (it is possible to design in multiple search spaces at the same time) search spaces along with several well-established design methods. The initial arrow points to where in the search spaces the design starts. For instance, the initial design point for a cognitive tutor method is figuring out the production rules for that domain (a mind design point). The full circles represent design points that are indicated by the design. For instance, in the TILT (tools, interfaces, learner's needs, and tasks) method first asks the designer to answer "what tasks need to be undertaken in the software?" (an activity design point) and then "what tools are provided to cope with those tasks?" (an environmental design point) (Soloway et al., 1994). The empty circles represent other design points that could be part of the design process. It is not always clear in which design space these points will be. Any design method is basically only a guide to starting off the design process and a trajectory to loosely follow. Eventually, designers have to do what is right for their design and all of these design methods simply become iterative design methods.

Medium-Based Design

> Man's use of mind is dependent upon his ability to develop and use "tools" or "instruments" or "technologies" that make it possible for him to express and amplify his powers. —Jerome Bruner (1966, p. 24)

We use designing a medium as a way to realize an environmentally-based design. Media theory tells us that a medium can have powerful affordances for learning; to borrow McLuhan's words, "the medium is the message." A medium is a way (as in the Bruner quote above) to amplify the powers of man (McLuhan, 1964). The computer as the first meta-medium, a medium to reinterpret previous mediums and create entirely new ones, provides a great vehicle for designing new media (Kay and Goldberg, 1977). The goal of MBD is not to use various media to convey some message independent of those media, but rather to design one medium so that it is the message. As such, the environment (the medium) becomes central to the design process. This is what separates MBD from the other design methods we mentioned. Part of the MBD approach is that you must investigate / explore what the message is of the medium you are designing. You often don't realize the full affordances of the medium until you have built it (diSessa, 1987). As such, a MBD designer cannot be solely ruled by the constraints of the problem, but must also take into considerations the constraints imposed by the solution (the medium). Taking the constraints of the solution space seriously and, at times, redefining the problem space to better match that solution space is something accomplished designers do often (Goel and Pirolli, 1992).

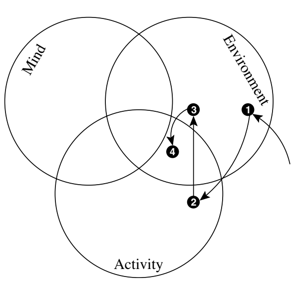
MBD starts with a medium that seems to address important learning goals. Next, the affordances of that medium for achieving those and other learning goals are explored. As such, MBD starts off in the environment search space—determining the learning affordances of a medium. Then, MBD proceeds by investigating the environmental needs and social context necessary for making those affordances recognizable and graspable. In a conventional approach, it is important to first clarify and investigate an important problem. Because MBD is environmentally based, this proves problematic. The designer may find that the medium actually support learning goals that are substantially different than that first intuition. Instead, in MBD, it is important to first clarify and investigate the solution—the medium. Solving an important learning problem is still essential to the goals of MBD, but that does not necessitate that the method have its initial focus on the problem. In both a conventional and MBD approach, solution and problem evolve together; the difference is that the initial focus is on the problem in the conventional approach and the solution in MBD.

In the next two sections, we will look at two learning systems (AudioExplorer and DigiQuilt) that were developed using a MBD method (see Figure 2). The design process for each of these systems is examined using the mind, activity, and environment search spaces. The reason to examine these systems is that they are similar in scope, yet different in approach. Both were implemented in Squeak, a system that is particularly effective for creating these kinds of media environments (Guzdial and Rose, 2002). Where they differ is that AudioExplorer is an inquiry tool, while DigiQuilt is a constructionist medium. These happen to be two large categories of constructivist learning systems, so the similarities between the two design processes should be applicable to a broader range of designs than just focusing on one type of learning system.

Figure 2: Using AudioExplorer to investigate the first six harmonics of a C note, Using DigiQuilt to create a quilt block design (actual 3rd grader's design)

AudioExplorer (an Inquiry Tool)

AudioExplorer is a computer environment to explore the physics of sound by examining the frequency domain (Rick, 2002). The frequency domain is a transformation of the sound signal into its frequency components. Since our ear perceives frequencies, examining the frequency domain is a useful way to understand the properties of music. The learning system consists of a music keyboard giving sound input into a computer (left half of Figure 2); the AudioExplorer software displays the signal on the screen, which can then be analyzed by the learners. Figure 3 diagrams the design process of AudioExplorer, highlighting the design points and the ideas that informed the design.



Idea A Use sonogram to investigate the 12 notes in one octave phenomenon
(1) Playing with various configurations of the sonogram and various sound inputs
(2) Playing with reflection in action as kind of apprenticeship
Idea B Compare instruments
(3) Playing with the multiple linked representations of the sound signal
Idea C Dyads working together to achieve convergent conceptual change
(4) Formative evaluation and redesign based on learner needs

Figure 3: Design Process for AudioExplorer

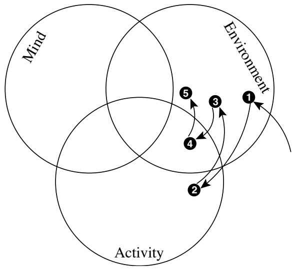
The idea for AudioExplorer came from a wish to explain why there are twelve half tones in an octave. Given the designer's background in digital signal processing, he (Rick) knew that this could be found out by investigating the frequency signal of harmonic sound. So, the solution was a medium for investigating the frequency signal (Idea A, Figure 3). Rick started playing around with Squeak's sound capabilities and various sound inputs (Step 1, Figure 3). Widgets for displaying sonogram (frequency signal over time) and spectrum (frequency signal at one time) graphs already existed. These widgets were tested with various sound inputs, including singing, playing music off a CD, whistling, etc. To capture lower frequencies with enough resolution, the size of the fast Fourier transform (FFT) was increased. In addition, both the spectrum and the sonogram graph were placed on the screen at the same time (this involved rotating the spectrum graph by 90 degrees). By hooking in a musical keyboard as input, the harmonics of the individual notes could best be analyzed. From there, an analysis tool was added so that the user(s) could investigate the frequency of individual harmonics and that frequency would be directly linked with the closest note on the keyboard. Because of the knowledge of signal processing, Rick knew that AudioExplorer could demonstrate the relationship between the linear (harmonics have frequencies that are integral multiples of the fundamental) and exponential (frequency of the fundamental increases exponentially with each octave) properties of harmonic sound (as can be found in music). Yet, it was not clear how learners would use the system.

Creating a tool that the designer can use to demonstrate the learning concepts might be a necessary first step, but it does not complete a learning system. Others would have to be able to engage the system in a useful way. To test out how others could engage the system, Rick, inspired by Schon's (1987) concept of reflection in action, conducted informal user testing (Step 2, Figure 3). He sat down with several people and showed them the system, letting them play around and helping them when necessary. In the end, this format proved awkward. Users were more interested in Rick demonstrating the concepts than in being guided towards figuring them out for themselves. Yet, it showed that only a little bit of appropriate guidance was necessary to allow users to engage the system.

Yet to be determined was what else this inquiry tool could be used for or how, where, and if it would be usable in a learning setting. Based on a suggestion from a fellow student (Idea B, Figure 3), the possibility for using the system to investigate the differences between instruments was researched and proved viable (Step 3, Figure 3). In this way, AudioExplorer became a system that linked multiple representations of the sound input; multiple linked representations have been found to be useful in previous systems in increasing learner's understanding (Kaput, 1989). Because the analysis tools (that showed the exact frequency) proved extraneous for this task, two usage modes were integrated into the system; the novice mode simply hid the analysis tools. Now, the learning goals could be clearly established. Based on Roschelle's (1996) work on dyads using an inquiry tool together, the learning situation became having two novices work together on an open-ended[1] laboratory assignments (Idea C, Figure 3). Finally, a proper setting for using the software was found—a "Physics of Music" class at Georgia Tech. For formative evaluation, two groups tested the system/laboratory assignment (Step 4, Figure 3); both groups achieved a good understanding of the learning goals (Rick, 2002). Based on this design step, several interface changes were made to the AudioExplorer software.

DigiQuilt (a Constructionist Medium)

DigiQuilt is a computer-based construction kit for learning about math and art by designing patchwork quilt blocks (Lamberty and Kolodner, 2002). The hierarchy of construction materials in the system is best described as pieces, patches, and blocks (which can be put together into quilts outside of the system). Users create quilt blocks by selecting colored shapes (pieces) from a palette and placing them into a grid (into patches), so the main mode of design is direct manipulation. The software currently offers learners 4, 9, or 16-patch work-spaces with a variety of grids that can be imposed on them, facilities for saving and reloading images, buttons for clearing the grid and stepping forward or backward through a design, a palette with shapes and buttons to change their colors, and facilities for rotating shapes or patches and copying or swapping patch-level designs so that they can be easily repeated or changed (right half of Figure 2). DigiQuilt has the learner move shapes to create the designs; much like a physical manipulative. The designs can be printed or saved easily, and provide context for discussions of the targeted concepts among the learners. Figure 4 diagrams the design process of DigiQuilt, highlighting the design points and the ideas that informed the design.



Idea A Use patchwork quilting as a medium for learning math
(1) Playing with manipulatives (Froebels gifts, pattern tiles)
Idea B Use a manipulative-based environment for design
(2) Try a challenge-driven approach (like LBD)
(3) Design software-based environment with (1) and (2) in mind
(4) Test of software in classroom with activities (design tools on the fly for helping students understand math through their designs)
(5) Further redesign based on previous experiences

Figure 4: Design Process for DigiQuilt

Designing DigiQuilt came from a desire to highlight the interesting math found in the world of patchwork quilt design (Idea A, Figure 4). The designer (Lamberty) noticed that patchwork represented a potential medium to explore many mathematical ideas, and further that quilting could be an interesting interdisciplinary link for math, art, and possibly history. Since elementary-aged students generally enjoy doing art projects, Lamberty thought patchwork design would provide a steppingstone from art to math for most, and from math to art for some. Either way, the hope was to increase the pool of interested students by combining two often disparate subjects.

Initially, the idea was explored using a paper version of the quilt-design manipulative that was designed based on Lamberty's experiences with other manipulatives (Step 1, Figure 4) to see what sorts of designs could be created and how to structure the activities (Idea B and Step 2, Figure 4). Early field tests showed that the kids had a tough time rotating the paper triangles the right amount to fit them into the square spaces of the grid. Since students could place shapes that overlapped the grid lines (or each other) in random ways, the resultant designs were difficult to talk about mathematically. If the learning goals were different that might not be a problem. But, since random overlapping created designs that were not so easy to talk about in terms of fractions, it had to be prevented. Thus, when Lamberty moved on to designing a software version of the manipulatives (Step 3, Figure 4), the shapes could be manipulated only in very specific ways. The shapes can only be turned 90 degrees, and they snap in place in the grid. Learners cannot place shapes that overlap grid lines using the software like they can in the paper version. Note, though, that given a different audience or set of learning goals, this might not have posed the same problem. The medium (patchwork) does not necessarily need to change with the audience, but the tools and constraints do need to change (since the learning goals do).

One feature of DigiQuilt was designed specifically to afford the learning of a listed standard for third graders: the ability to recognize the same shape in a different orientation. By presenting each shape on the palette in only one orientation and requiring students to rotate them to fit their needs and solve the challenge, the software affords learning to recognize the same shape turned in different ways. With a physical manipulative, where shapes are scattered on the floor or table, it is possible to select a shape without this recognition.

For the first classroom trials of DigiQuilt (Step 4, Figure 4), students used both the paper and computer versions of the manipulatives. In the study, student use of the paper version of the manipulative helped uncover several changes that might improve DigiQuilt and specify or extend the learning goals it could address. Using the paper version, it was easy to create and test a variety of methods for supporting students as they explored fractions and symmetry through their designs. One tool that came from this exploration was the "select-a-grid" tool. Challenges that involved equivalent fractions were difficult for students to understand. For example, when approaching the challenge, "create a quilt block that is 1/2 yellow, 1/4 red, and 2/8 blue," students ran into several difficulties. Some students did not understand that the 3 numbers added up to 1 and would result in the whole quilt block being filled. Some students began by filling the quilt block with 1/2 yellow, and then filled 1/4 of the remaining space with red. Since this didn't leave 8 squares behind, some students put a blue piece in the design. Lamberty thought that perhaps what was happening was that students needed to understand that each fraction referred to the whole quilt block. In order to help the students refocus their attention, she drew heavy lines on a paper 16-patch grid: first just one heavy line to emphasize 1/2, then another line to emphasize 1/4, and finally enough lines to break the design into 8 equal parts so the students could finish the design with the 2/8 blue. The select-a-grid tool adds support for student learning by highlighting connections between fractions in the challenges and the designs the students make. The main purpose of this tool was to help learners refocus their attention on the "whole" as they work on different aspects of the challenge, but the grids with lines that can also be lines of symmetry are also useful reference points for students as they attempt to solve challenges that involve symmetry.

Since that initial classroom fieldwork, several changes to the software have been made and tested (Step 5, Figure 4), and several new changes will be tested in the classroom throughout the coming school year. Current research on DigiQuilt focuses on studying student engagement over time in order to understand more about what kinds of tools are best introduced at what times, and describing the results of different attempts to get and keep students engaged. Over time, changes made to the system tend to be adding or improving *learning* supports (in response to user-testing) to highlight interesting connections between the medium (quilting) and the targeted content area (fractions), or adding new features that support the activity of *design* by simplifying the process of making changes or adding more options to the system.

The Design Process and the Designed Product

There are several design guidelines to be learned about designing constructivist environments from these two examples. (1) Start with a medium you know and care about. (2) Design by via negativa (solution in search of problem). (3) Explore the medium to clarify the solution space. (4) Built appropriate tools to accommodate different learning goals.

For both Rick and Lamberty, the media they started off with (harmonic sound and patchwork quilting) were far from arbitrary. Both care deeply about their medium, showing an interest and fascination with that medium far before the design process had started. For a bricoleur method of design, it is advantageous to have an affinity (or closeness) to the object to be manipulated. Through these systems, the designers were able to share that personal connections with others.

AudioExplorer had a specific problem in mind that allowed a larger problem space to be found from that specific problem. DigiQuilt had a broad problem in mind and then used specific standards and audience to focus in on a more specific solution. If the strength of the problem-first design process is knowledge of the problem space, the strength of the via negativa design process is knowledge of the solution space. Both processes involve scientifically rigorous investigation of a search space and are therefore not arbitrary. For DigiQuilt, physical manipulatives were used to explore the design space. Because of their flexibility, adaptability, and familiarity, physical versions accelerated the exploration of the solution space and allowed for the search to be highly iterative. For AudioExplorer, early versions were demonstrated to many knowledgeable users, including experts in the domain (audio, music and signal processing) and educational technology. The system already addressed the original problem and, by the help of others, the solution space was better illuminated.

It is not coincidental that both DigiQuilt and AudioExplorer have different user modes. The different modes accentuate different parts of the medium and thus address different learning goals. In each, the tools that were built to manipulate the medium addressed specific learning goals. In AudioExplorer, the analysis tools allowed learners to move from investigating instruments to investigating the mathematical properties of harmonics. In DigiQuilt, the rotate and copy tools helped children meet listed standards. If the second guideline can be summarized by "the medium is the message (McLuhan, 1964)," then this third guideline can be summarized by "we shape our tools and they in turn shape us (McLuhan, 1964)."

On top of these design guidelines, there are also some interesting similarities in the end product of these environments. The main one is that they are more like tools (AudioExplorer as a kind of specialized oscilloscope) and media (DigiQuilt as a kind of quilting medium) than traditional computer applications. In each, the computational nature only helps the process. So, both realize Kay and Goldberg's (1977) vision of computer as a tool for creating new media by reinterpreting old media (harmonic sound and patchwork respectively). This may be a feature shared by many constructivist learning environments. Second, both are systematically elegant/simplistic (a few features go a long way).

Endnotes

(1) Participants were asked to complete such open-ended assignments as comparing several instruments to each other and writing down any five interesting observations that they made about the differences.

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