Medium-Based Design: Extending a Medium to Create an Exploratory Learning Environment*

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Abstract

This article introduces *medium-based design*—an approach to creating *exploratory learning environments* using the method of *extending a medium*. First, the characteristics of exploratory learning environments and medium-based design are described and grounded in related work. Particular attention is given to *extending a medium*—medium-based design's core method. Then, the product and process of two environments are detailed to show how medium-based design enables the creation of exploratory learning environments. Finally, a study compares medium-based design to a conventional design process to test the hypothesis that medium-based design is particularly effective in creating exploratory learning environments.

1 Exploratory Learning

In an elementary school classroom, a fourth grader uses a computer program to design a quilt with the challenge to cover $\frac{1}{3}$ of the quilt block with one color and $\frac{2}{3}$ with another color. He struggles for some time using a 4-by-4 grid. Eventually, he raises his hand and remarks to the researcher with an emphatic and confused look, "I think it's really *hard* to make one third." Indeed, with the pieces provided, it's impossible. The researcher agrees with him and suggests that he try showing $\frac{1}{3}$ using a 3-by-3 grid.

At a university, two physics-of-music students examine the spectral output of a musical keyboard using a computer program. Surprisingly, the same note played with the organ looks different than played with the piano—there's an extra harmonic above the fundamental. After some experimenting and reflecting on their own experience, it clicks for one of the students. "Oh! It's because you're getting this pedal tone [points to a harmonic *below*

*This article was published in the journal *Interactive Learning Environments* (2005), 13(3):179–212. Interactive Learning Environments is available online at: *http://journalsonline.tandf.co.uk/link.asp?id=r75qwn2k67g4*

the fundamental] and that [extra harmonic *above* the fundamental] is a harmonic of that." Using the program, she explains it to the other student.

Both of these are examples of *exploratory learning*—learning that occurs through learner-driven reflective inquiry. Instead of being passive consumers of information, learners are active explorers of their own understanding. In education, learning by inquiry has a long history of being championed by theorists, such as Dewey (1938), Fröbel (the originator of Kindergarten), and Montessori:

> Both Fröbel and Montessori emphasize the importance of assisting this "little explorer" in his researches. With the former this is to be accomplished by the direct help of the adult; with the latter more indirectly by means of a "prepared environment" so simplified and set in order that the objects in it easily and systematically reveal their qualities to the inquiring mind of the little scientist. (Standing, 1957, p. 327)

Like in Montessori's system, the learners in our two examples are supported in their inquiry by the environment. They are environments where learners can act as explorers and discover the principles of a certain domain. In both cases, the exploration in the environment yields *expectation failure*—learners expect something to occur, but what actually occurs fails to meet those expectations. Expectation failure is particularly important to learning as it allows learners to reflect on their own understanding (Kolodner, 1997). In the quilt example, the learner asks the researcher for assistance to resolve his problem; in the organ example, the learners resolve their problem using previous knowledge and the affordances of the environment. In both cases, the learning environment enables learners to reflect on their exploration and thereby build their understanding.

In this article, we concern ourselves with these *exploratory learning environments*—environments that enable learner-driven reflective inquiry. We are interested in both the product—what makes for an effective exploratory learning environment (ELE)—and a process to support the creation of such environments. Based on previous research, we characterize six defining properties of effective ELEs. While we are able to characterize ELEs from that literature, a formalized grounded-in-theory approach for creating ELEs is missing. We articulate and ground such an approach. Drawing on media theory (McLuhan, 1964; Bolter & Grusin, 1999; Kay & Goldberg, 1977), *medium-based design* (MBD) uses the technique of extending a medium to create an ELE.

This article is organized into five body sections, concentrating on our goal (ELEs), our approach for achieving that goal (MBD), and the method by which we do it (extending a medium). First, we synthesize previous research to characterize ELEs. Second, we detail the important phases of MBD, grounding them in theory. Third, we demonstrate the power of MBD's core method of extending a medium. Fourth, we demonstrate how MBD can be used to create effective ELEs by examining two environments, DigiQuilt and AudioExplorer, designed with MBD. Fifth, we test our hypothesis that MBD is a particularly effective design method for creating ELEs. After these body sections, we conclude by discussing the affordances and limits of our approach.

2 The Goal: Exploratory Learning Environments (ELEs)

In this section, we more closely define what we mean by an exploratory learning environment. An ELE is an environment that supports learners in constructing their understanding about a specific subject through learner-driven reflective inquiry. We synthesize related threads in the literature to arrive at six characteristics of an effective ELE. The first four (empty, open-ended, structurally simplistic, and concrete) are sufficient for an environment to be an ELE. The last two (personal connections and epistemological connections) are necessary for the ELE to effectively engage both the learner and important subjects. Naturally, we are interested in producing effective ELEs—those that meet all six characteristics.

We do not argue that all learning environments should be ELEs nor that all effective learning environments are ELEs. There are many examples of effective learning environments that fail to meet some or all of these characteristics. Instead, we argue that these characteristics define a useful class of environments to support exploratory learning. We argue that it is the combination of the characteristics that has specific power, more than the sum of its parts; therefore, it is useful to define ELEs as a separate class.

We do not argue that all learning should be learner-driven and can be solely supported by the learning environment. Social interaction, such as teacher or expert guidance, is extremely important to learning. Even in an effective ELE, there is still a need for social support (Bruckman, 1998); although, the nature of that social support changes. In exploratory learning, the focus is on the learner learning, rather than the teacher teaching. This does not mean that the teacher is unimportant. The teacher is still important, but the role changes from being a "sage on the stage" to being a "guide on the side." Instead of being the transmitter of information, the teacher acts as a guide to assist the learners' inquiry.

In education, ELEs have a substantial history. They have been championed by educational theorists (Bruner, 1966; Zucchermaglio, 1993) and educational technologists (Papert, 1993a; diSessa, 2000), under classifications such as microworlds (Papert, 1987), construction kits (Resnick, Bruckman, & Martin, 1996), media creation tools (Kay & Goldberg, 1977), and inquiry tools (Soloway, Guzdial, & Hay, 1994). Part of what makes ELEs useful as a class of learning environments is that it is broad enough to encompass a broad range of previous work, yet narrow enough to have definable characteristics. We start by detailing the four sufficient characteristics (empty, open-ended, structurally simplistic, and concrete) for an environment to be considered an ELE:

Empty An ELE is *empty* of content; the learner "fills" it to establish its meaning.

Zucchermaglio (1993) broadly categorizes learning environments[1] into two groups: empty and full. Full environments are *full of content* for the learner to absorb. In contrast, empty environments do not contain explicit content. Instead, the message of the empty environment is only realized when it is engaged by the learner.

[1] Zucchermaglio actually uses "technology," instead of "environment." In this research, we do not believe that technology (or implicitly *new* technology) deserves special treatment from previous technologies. After all, it is only in relationship to humans that old and new technologies achieve their meaning.

Full environments, such as the majority of Computer-Assisted Instruction and Intelligent Tutoring Systems, are designed under the premise that learning is a process of transferring content from the environment to the learner (Zucchermaglio, 1993). The full environment acts as a repository for content; the content is transferred to the learner. In contrast, empty environments are based on a constructivist model of learning, where learners construct their own understanding (Zucchermaglio, 1993). The learner engages the environment to construct meaning.

For example, a textbook is a full environment. It is full of content for the learner to absorb. The message of the textbook is its content. In contrast, a coloring book is an empty environment. The learner engages it by filling it with color. The message of the coloring book is the skill the reader achieves by engaging it. At the end of the learning process, the content of the textbook is unchanged from reading, while the content of the coloring book is largely constructed by the learner.

Another example of the difference between empty and full is that of piano versus stereo. The piano is empty; a player must actively engage it to produce music. The stereo is full; a listener passively engages it to consume music. As a learning environment to foster inquiry, the piano is more promising than the stereo (Resnick et al., 1996).

Open-Ended The interaction facilitated by ELEs is *open-ended*; the learner chooses how to explore.

This characteristic addresses learner control. Is the learner in control of his or her learning process? ELEs are open-ended—the learner is significantly in control of their own learning process. Learners can use them at different rates and in different ways. As such, they can support different ways of approaching subjects, which is important as people learn in different ways (Turkle & Papert, 1991).

In many common learning environments, learner control is non-existent or superficial; it is the environment that is in control (Papert, 1987). Consider an educational television show or a typing tutor. In an educational television show, the learner has no real choices about the information being transmitted or the style of interaction. Learner control is non-existent. In a typing tutor, the learner has significant interaction (typing in letters) with the tutor, but the tutor is in control of the content (letters to type, difficulty, level, assessment, etc.). Any sense of learner control is superficial.

In contrast, either a coloring book or a piano allows for open-ended interaction. One person can concentrate on drawing within the lines. Another person can concentrate on using matching colors. One person can concentrate on learning classical piano technique. Another person can concentrate on using fake books[2] to play popular hits for singing along with. For both a coloring book and a piano, the learner has a real choice of how they engage the environment.

While ELEs can be characterized as open-ended, their use need not be totally unrestricted. For instance, it would be foolish to sit a novice in front of a piano and expect them

[2] A *fake book* contains condensed information about songs (lyrics, melodies, and chord progressions). It is used by musicians as an abridged substitute for standard sheet music.

to learn to play beautiful music by themselves. Appropriate challenges, such as playing a particular piece of music, and guidance can aid the learning process tremendously. Yet, the piano allows the type of challenge and guidance to be influenced by the desires of the learner.

Structurally Simplistic An ELE is *structurally simplistic*; in the environment, the learner engages a few powerful structures and strictures.

Simplicity has been touted as an important concept in design. In user-interface design, simplicity is often seen as a fundamentally good property (Norman, 1988). Here, we hope to go beyond simplicity in interface. ELEs are simple in a specific way—they are structurally simplistic. This is a term we take from diSessa's (1985) descriptions on how he designed the Boxer computation system. To assure that users can accomplish many things while only mastering a few structures, diSessa made structural simplicity an explicit goal of his design.

ELEs are characterized by a few fundamental *structures* (constructs) and *strictures* (constraints). In an ELE, the learner masters the environment. Having few structures and strictures enables that mastery to be accomplished. Mastering the fundamental structures and strictures of the environment allows learners to grasp the embodied concepts—to learn. A good exploratory learning environment has only a few structures and strictures that offer powerful affordances for learning, while simultaneously being simple enough to master. In other words, the structures and strictures should offer a good payoff for effort. One way they often offer a good payoff for effort is that they afford multiple representations of the fundamental structures. Different representations can have different affordances for learning, so providing multiple representations (often simultaneously) is useful for learning (Suthers & Hundhausen, 2003; Kaput, 1989). Because there are a small number of fundamental structures, it is possible to represent them in different ways.

Consider the piano. It is structurally simplistic. It has a limited amount of structures. Even on full-size pianos, there are only 88 keys to strike. Furthermore, those keys are organized into octaves, with the black-and-white-key pattern repeating every 12 keys (i.e. one octave). It has a limited amount of strictures. Each key is restricted to a single fundamental frequency. There are plenty of musical tones between C and C#, but the piano does not allow you to play them; other instruments, such as the violin, would. Of course, the success of the piano is not just because it has structures and strictures, but because those structures and strictures map to qualities we look for in western music. The notes played by the piano keys are the ones used in western music. Even the black-and-white-key pattern is representative of western music—a piece of music restricted to the key of C major or A minor only uses the white keys. So, when learning about music, it is useful to start with a piano, rather than an entire orchestra (Rick, 2002b). The orchestra is much more complicated than the piano and that complexity would obscure those structural connections to western music. In contrast, the piano is simplistic in such a way to have obvious structural connections to the nature of western music.

Concrete An ELE offers *concrete* connections to important concepts; the learner is able to reflectively engage the concepts in the environment.

A domain of study can often be represented in an abstract hierarchy, with concrete instantiations at the bottom of that hierarchy. Justified by a striving towards incremental learning, some draw the conclusion that the abstractions should be learned first. Intuitively, it seems easier to first teach the abstractions, so that this knowledge can be transferred to the instantiations. In this top-down approach to learning, learners first address the top classifications (or abstractions) and then move down the hierarchy to the instantiations (concrete examples). But, it is often the objects at the bottom of that hierarchy with which we are most familiar and have the most connections. As such, we can draw upon those previous connections to understand the more abstract concepts (Wilensky, 1991). Learning research has recently revalued concrete ways of learning and shown that starting from the concrete with a bottom-up process can be useful (Kolodner, 1997; Turkle & Papert, 1991). ELEs, in essence, enable the learner to use these concrete connections as a bridge to the more abstract concepts. As part of the inquiry process, learners engage the domain of study concretely in the environment.

Consider learning about heat conductivity from a laboratory experiment versus learning it from a book. While they might cover the same material, the laboratory experiment represents the material in a concrete manner, while the book represents the material in an abstract manner. Besides having hands-on experience with relevant materials, the laboratory experiment has the advantage of allowing for reflection and expectation failure. Learners can try something to test their understanding. So, ELEs are concrete to facilitate reflective inquiry learning.

So far, we have characterized ELEs as empty, open-ended, structurally simplistic, and concrete. While some of these characteristics could be viewed independently as beneficial, we feel that there is a strong synergy between these characteristics. Just because an environment is empty does not mean that inquiry learning will occur. Just because an environment is open-ended does not mean that learners will use it in a way that is useful to their learning style. The structures and strictures the learner engages have to embody concrete connections to the subject in order for the exploration in the empty open-ended environment to be fruitful. Because exploratory learning environments are meant to be mastered (due to their structural simplicity) and are empty, they allow for open-ended use that can be quite motivating for the learner. The learner can chose what to explore, construct, or analyze. They can do that in a way that is personally interesting to them.

While these four characteristics are sufficient for an environment to be considered an ELE, this does not guarantee that it is an effective learning environment. Consider the piano. It meets the four characteristics. Yet, it is doubtful that simply sitting a novice in front of a piano will lead to useful learning. This is all the more true if the learner is unfamiliar with western music. To address effectiveness for a given learning situation (environment, learners, social interaction, setting, etc.), two other characteristics are added, based on work by Resnick et al. (1996). While they champion these characteristics for construction kits, we believe they apply to all exploratory learning environments.

Personal Connections An effective ELE is able to leverage previous interests and experiences to connect new concepts to pre-existing concepts (knowledge, intuitions, etc.).

Epistemological Connections An effective ELE is able to address important concepts (domains of knowledge, ways of thinking, etc.) through natural exploration (inquiry, construction, etc.).

In the case of the complete novice, the obstacle to the piano being an effective ELE is that the novice needs more support than is provided in the environment to usefully leverage previous interests and experiences. In contrast, an experienced composer may find that a bare piano is all that is necessary to explore and create new music. To be effective, an ELE needs to be both appropriate to the learners (personal connections) and to the subject (epistemological connections).

2.1 ELEs as Scaffolding Sense-Making

ELEs may be a new concept (in this classification anyway), but the support they provide for learning has already been established. To further that argument, we show how the characteristics of ELEs address the three sense-making guidelines in Quintana et al.'s (2004) framework for scaffolding science inquiry learning.

1. *Use representations and language that bridge learners' understanding.* Because of their structural simplicity, ELEs can link representations to increase learner understanding. The concrete nature of ELEs allows learners to manipulate things they are familiar with to engage more abstract domain concepts. Because of their personal connections, ELEs leverage previous experiences to connect the new concepts to preexisting ones, thereby bridging learners' understanding.

2. *Organize tools and artifacts around the semantics of the discipline.* Because of their concrete connections to important concepts, ELEs allow learners to engage disciplinary concepts while engaging in the kind of open-ended exploration common to science disciplines.

3. *Use representations that learners can inspect in different ways to reveal important properties of underlying data.* Much of what an ELE tries to accomplish is to allow the learner to explore new aspects of the environment through a variety of lenses or tools. Because of their empty and open-ended nature, ELEs can be used in different ways. Because the lenses focus the learner's attention in different ways, they reveal important properties of the underlying environment.

While the correspondence is not one-to-one, the characteristics of ELEs match well to the guidelines that Quintana et al. posit for supporting science inquiry. Not all exploratory learning is inquiry science learning, but the two seem to be congenial. By showing that ELEs address important goals in supporting inquiry science learning, we aim to show that ELEs may be of interest to that established research community.

2.2 Demarcation: ELE's Boundaries

So far, we have woven several intellectual threads together to form our ELE classification. Consequently, it is no surprise that the category is rather broad, covering under its umbrella what others have termed microworlds, construction kits, inquiry tools, and media creation tools. What are the boundaries of the ELE category?

Like other important dimensions in education (Reeves, 1994), the boundaries of the individual characteristics are fluid. Environments span the range from being empty to being full, from being open-ended to being constrained, from being structurally simplistic to being complex, and from being concrete to being abstract. Consequently, the boundaries of the ELE category are fluid as well—there is no definitive boundary. Instead, we define a loose boundary: effective ELEs are the group of environments that meet all six characteristics to a fair extent. As the characteristics interact, it is more important that an environment meets all characteristics than that it excels in a subset of them.

Many of the six defining characteristics have been touted by their originators to apply to a broad class of learning environments. Zucchermaglio (1993) prefers empty environments. Kolodner (1997) advocates a concrete approach. As their arguments have merit, it is only natural that many effective learning environments meet their characteristics. Yet, an effective environment can meet some of our characteristics and fail to meet others.

For instance, goal-based scenarios (Schank, Fano, Bell, & Jona, 1994) explicitly feature concrete connections; however, they are not empty. Much of the knowledge gained from using a goal-based scenario is a consequence of the scenario being full of content. So, goal-based scenarios are not ELEs. Similarly, many collaborative learning environments, such as CoWeb (Guzdial, Rick, & Kehoe, 2001) and CSILE (Scardamalia & Bereiter, 1991), are empty, open-ended, and structurally simplistic; however, as domain-independent collaboration tools, they do not offer concrete connections to specific learning goals. They are not ELEs.

By classifying these environments outside the ELE umbrella, we do not mean to question their effectiveness or marginalize them. To the contrary, we offer them as examples of effective learning environments that are not ELEs. It is not necessary for an environment to be an ELE to be an effective learning environment. Yet, we do believe there is value to being an ELE.

2.3 From Goal to Approach

As designers, we are interested in creating effective ELEs—that is our goal. In this section, we detailed the characteristics of that goal. While knowing these characteristics allows us to identify ELEs and reflect on whether our design meets these characteristics, there is more to effective design than that. If designing an ELE is similar to creating a movie, knowing the characteristics of ELEs is similar to being able to identify the properties of a good film. It may be necessary to make a good movie, but it is not sufficient. The approach towards that goal is anything but clear. In the next session, we describe an approach (MBD) that we have found useful for achieving our goal (creating ELEs).

3 The Approach: Medium-Based Design (MBD)

> Making the simple complicated is commonplace; making the complicated simple, awesomely simple, that's creativity. —Charles Mingus, Jazz composer and bassist

By their nature, exploratory learning environments are simple. Unfortunately, simplicity is hard to design for; it takes creativity. Many learning environments suffer from too many features. One reason for this is that a conventional problem-based design approach tends to add more structures and strictures over time. As more are added, those structures and strictures lose their simplicity and thereby their conceptual coherence. ELEs need to be structurally simplistic; unfortunately, a conventional hard-style design makes simplicity a hard goal to achieve. So, we are offering an alternative approach that, in our experience, is useful for designing ELEs.

Turkle and Papert (1991) note how learners approach tasks with two distinct styles: a *hard* and a *soft* one. Conventional design methods have valued a hard-style approach, neglecting the soft-style designer. The soft style is different from but not worse than the hard style (Turkle & Papert, 1991). The hard style is a structural and top-down approach. The large problem is divided into smaller more-manageable problems; solving the smaller problems solves the larger problem. In contrast, the soft style is bottom-up and negotional. It involves a closeness to objects. While hierarchy and abstraction are valued by the structured problem solvers, these *bricoleurs* prefer negotiation and rearrangement of their materials (Turkle & Papert, 1991). Traditionally, the hard style has been given a higher status, while the soft style has been maligned. Yet, the soft style too has its advantages; even in Western science, where a distance from the object of study has been strongly encouraged, there are examples of breakthrough success using a soft style (Turkle & Papert, 1991).

Our design method, medium-based design, offers designers an alternative—a soft-style approach to designing learning environments. MBD extends a medium to create an ELE. We draw on media theory (McLuhan, 1964; Bolter & Grusin, 1999) to realize the power of a medium (a way of creating, consuming, and transmitting information) to have a message to those that engage that medium. We draw on the power of the computer to create new media (Kay & Goldberg, 1977) to realize the potential of a new medium as a learning environment.

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 MBD and providing guidelines that follow this approach, we are showing support and value for this approach. This section describes the four important phases of MBD, grounding each in media theory.

Phase 1 Begin by choosing a medium you know well, care about, and feel has learning potential.

> 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. (Bruner, 1966, p. 24)

A medium is a way (as in the Bruner quote above) to amplify the powers of man (McLuhan, 1964). We base our design on that medium, in an effort to harvest the powers of the medium for learning. From there, we seek to realize an exploratory learning environment.

MBD is a soft style of design. We aim not to hide this, but rather to embrace it and use it to our advantage. So, the MBD designer should start with a medium that they are close to—they understand it and care about it. This closeness is an asset as *the designer is seeking to create an environment that has personal connections to the learners who use the environment*. To better illustrate our notion of closeness, consider Papert's (1993b, preface) fond recollection of the differential gear. As a child, he (to use his words) fell in love with the differential gear and the mathematical concepts it embodied. He connected new concepts to the differential gear; the differential gear became a powerful medium for him to understand his world. For Papert, the differential gear is a medium he is close to—he knows it well, cares about it, and feels it has a learning potential. It is that kind of closeness to the medium we are looking for.

Phase 2 Explore the medium to understand its affordances for promoting learning.

> The medium is the message. (McLuhan, 1964, p. 7)

What McLuhan means by his infamous proclamation is that "societies have always been shaped more by the nature of the media by which men communicate than by the content of the communication" (McLuhan & Fiore, 1967, p. 8). The nature of the media by which we communicate not only carry content, but also carry a message independent of the content we try to communicate. That message is important to the individual engaging the medium; it works him or her over completely (McLuhan & Fiore, 1967). The medium has affordances and the message to the individual is strongly affected by those affordances.

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*. Yet, the affordances of a medium are not inherently obvious. In particular, the importance of a new medium is often not discovered until it has been used for a while (McLuhan, 1964; Bolter, 2001). People tend to fit the affordances of established seemingly-related media into the new medium; through this process they discover the unique affordances of the new medium (Bolter & Grusin, 1999). For instance, early cinema was often hardly more than filmed stage theatre; over time, film evolved into its own genre. Understanding a new medium is a journey of discovery that requires serious exploration.

Consider diSessa's (1987) enhancement to Logo. Traditionally, Logo allows users to program a digital turtle to draw shapes on the monitor screen, a 2-dimensional plane. diSessa wondered if anything could be gained by mapping the 2-dimensional plane onto a 3-dimensional cube. Mathematically, it was doable; however, it was not clear that the new environment would afford any new uses. For several weeks, he experimented with the idea on paper, finding no useful differences; turtles behaved the same in every scenario he imagined. Consequently, he became discouraged with the idea. As a last resort, he implemented a working prototype. Almost immediately upon completing the prototype, he discovered several interesting differences. For instance, if the turtle was positioned properly near the corner of the cube, it was possible to draw a triangle using three 90-degree angles. diSessa was only able to realize the affordances of his new medium after he built it. Only after he built it could he properly explore it.

Fundamental to MBD is that the designer must explore what the message is of the medium they are working with. As with any design process, this must be a reflective practice (Schön, 1987). The designer must explore what the medium is good for. In our experience, this exploration cannot be done theoretically. The designer must actually play with the (new) medium and try to figure out what the affordances are. In practice, this involves building prototypes (implementations that work to a certain extent). These prototypes must be sufficiently developed and useful to allow the designer to actively explore (and even extend) the medium.

Phase 3 Extend the medium to change those affordances.

> We shape our tools and they in turn shape us. (McLuhan, 1964, p. xxi)

It is our experience that differences in a medium can create large differences in its affordances for learning. In essence, extending a medium creates a new medium with different affordances (McLuhan, 1964). So, it is the MBD designer's task to *extend the medium (shape the tools) so that important learning goals (how it shapes us) are realized*. Extending a medium is the primary method of MBD on both a large and a small scale.

Large extensions extend the medium along a fundamental (physical, temporal, or quantitative) dimension. Typically, they dramatically alter the learning affordances of a medium. Consider, for instance, extending a video camera along a temporal dimension. A standard video camera captures 30 frames per second; this is useful for recording real-time events. In contrast, a time-lapse camera may only capture one frame every five minutes; this is useful for recording large-scale events, such as the lunar cycle (Terry, Brostow, Ou, Tyman, & Gromala, 2004). As a learning tool, the time-lapse camera focuses the user on a different subject than the video camera.

Small extensions change the medium by adding new structures (constructs) and strictures (constraints). Typically, they highlight specific learning goals. Different modes can focus a learner on different aspects of the subject. A new lens can offer a new representation for the learner to connect with (Kaput, 1989).

Because of its importance to MBD, extending a medium will be further detailed in this article. Section 4 details two examples of how extending a medium works on a large scale. Section 5 details how this method functions on a small scale as we detail the design of two ELEs created with MBD.

Creating a medium and realizing its affordances in ways that others will be able to engage them is a difficult task. Fortunately, adding computation gives us additional flexibility in designing media (Resnick, 1998). 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 & Goldberg, 1977).

Phase 4 Transition from the solution (the medium) to the problem (a clear message).

MBD proceeds by investigating the environmental needs and social context necessary for making those affordances recognizable and graspable. In a hard-style design process, it is important to first clarify and investigate an important problem. In contrast, the MBD designer may find that the medium actually supports learning goals that are substantially different than that first intuition. As such, the MBD designer cannot be solely ruled by the constraints of the problem (the message), but must also take into considerations the constraints imposed by the solution (the medium). Therefore, in MBD, it is important to first clarify and investigate 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 & Pirolli, 1992). 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 hard-style design and MBD, solution and problem evolve together; the difference is that the initial focus is on the problem in the hard-style design and the solution in MBD.

The closer a design comes to fruition, the less it can be dependent on MBD, or any design method, whether it be hard or soft. The situation matters (Lave & Wenger, 1991). As a learning situation can be realized into concrete scenarios (Carroll, 2000), the specific needs of that learning situation (students, teacher, school, etc.) become primary. At that point, designers have to do what is right for their learners' needs (Soloway et al., 1994) and the design process can best be characterized as learner-centered iterative development. Sometimes, the medium is not enough and other learning supports will need to be added (Joseph & Nacu, 2003). Social and process support may be needed to support the environmental affordances (Quintana et al., 2004). For example, in MOOSE Crossing (an on-line community for kids to share their creative writing through programming), the on-line community provides both motivation and learning support for its members (Bruckman, 1998).

4 The Method: Extending Media

One of the foundations of MBD is that extending a medium is a powerful way of creating a learning environment, since the extended medium has different affordances for learning than the original medium. In this section, we aim to demonstrate this with two cases. In the first, we examine two physical manipulatives: fraction sticks and algebra rectangles. In the second, we examine two computer-based learning environments: Logo and StarLogo. In each case, one medium extends the other leading to different learning goals being addressed by the learning environment. We detail both a physical manipulative and a computer environment to show that the principle of extending a medium applies to all media, from simple blocks to sophisticated programming languages.

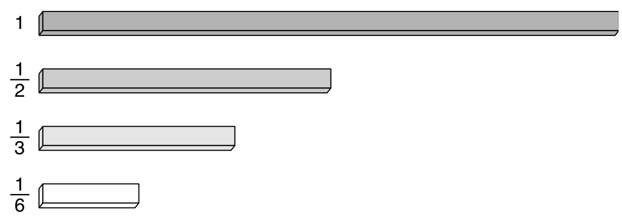

Figure 1: Fraction Sticks—different lengths represent different fractions

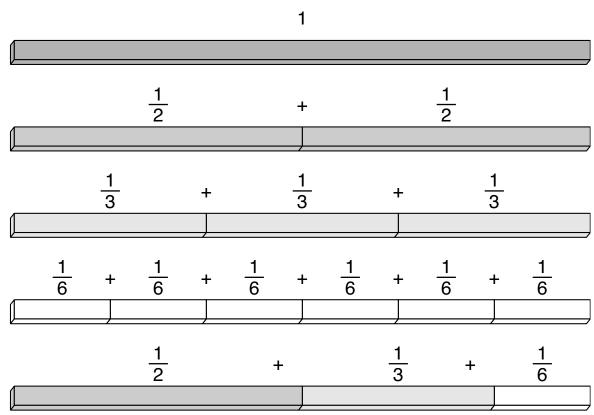

Figure 2: Examples of how 1 can be split up into fractions using Fraction Sticks

4.1 Example 1: Sticks and Rectangles

Fraction sticks (see Figure 1) are sticks of various lengths that represent different fractions with their length (the height and width are the same for all sticks). So, a fraction stick representing $\frac{1}{3}$ is twice the length of a stick representing $\frac{1}{6}$. Fraction sticks are easy to align end-to-end. Combining fraction sticks in this manner essentially creates a new fraction stick whose value is the sum of its component sticks. So, the sticks afford easy (visual) addition. Also, they afford comparing, as it is easy to see that one stick is longer, shorter, or equal to the length of another stick by laying it next to the other stick. Visually, a $\frac{1}{2}$ stick is larger than a $\frac{1}{3}$ stick, like $\frac{1}{2}$ is a larger fraction than $\frac{1}{3}$. As learners play with these sticks, they can see how various fractions compare to each other. Combining these two affordances, learners can see how the sum of various fractions compare to each other (see Figure 2). So, it is easy to see that three $\frac{1}{3}$ sticks and two $\frac{1}{2}$ sticks have the same length, or, mathematically, that $\frac{1}{3}+\frac{1}{3}+\frac{1}{3}=\frac{1}{2}+\frac{1}{2}$.

Mapping fractions to the lengths of these sticks creates a useful medium that affords learners to encounter important learning goals for fraction learning—how fractions compare to each other and how the sum of these fractions create new fractions. Other themes can be usefully mapped to these sticks. Cuisenaire rods, for example, are very similar (rods differ

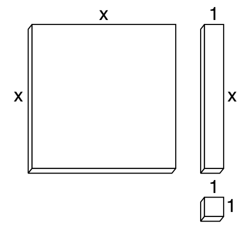

Figure 3: Algebra Rectangles—different areas represent different quantities (a x by 1 rectangle has an area of x)

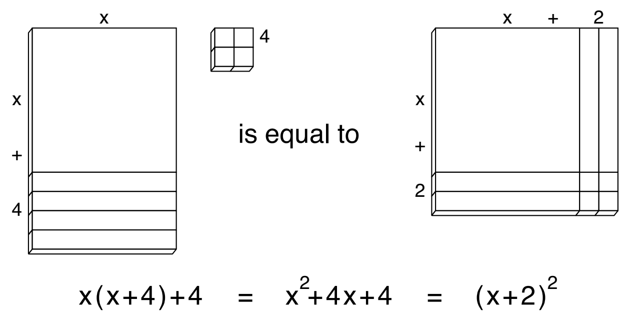

Figure 4: Using Algebra Rectangles to show that different equations are the same

in length), but they are not necessarily mapped to fractions. Yet, fractions work well as there is a clear and simple mapping between the learning goals (addition and comparison of fraction) and what the medium affords (addition and comparison of lengths).

Fraction sticks differ in one dimension—their length. One way to transform a medium into a different medium is just to *extend* a dimension. A simple dimension to extend is a physical dimension. Here, we look at what happens when we extend the width. The sticks are converted into rectangular blocks that share the same height, but differ in length and width. Whereas sticks afford thinking about length, rectangles afford thinking about area, the product of the length and the width.

When Bruner (1966) uses these kind of rectangles, he does not map fractions to the dimensions, but chooses to use whole numbers and algebraic symbols (see Figure 3). Since areas of rectangles are determined by the products of their length and width, these algebra rectangles afford multiplication. 4 can be represented by four 1-by-1 rectangles. The symbol x can be represented by an x-by-1 rectangle. The symbol x^2 can be represented by an x-by-x rectangle. In Bruner's use, the learners are not concerned with solving for x, but rather in using it symbolically. So they can construct equations visually that can then be converted to algebraic equations (see Figure 4). As area is retained when the shapes are rearranged, these rectangles afford thinking about equalities. Using Bruner's algebra rectangles, learners can explore algebraic equalities.

Mapping numbers and algebraic symbols to the length and width of these rectangles creates a useful medium that affords learners to encounter important learning goals of algebra—how simple algebraic expressions can be multiplied. The algebraic theme works well as there is a clear and simple mapping between the learning goals (multiplication of simple algebraic expressions) and what the medium affords (rearrangement and decomposition of rectangles by area).

Though these two media (fraction sticks and algebra rectangles) are very similar morphologically (the one extends the other into another physical dimension), they are quite different in their learning goals. Fractions sticks afford learning about the addition of fractions. Algebra rectangles afford learning about the multiplication of simple algebraic expressions. Not only are these different learning goals, but the learning goals are of interest to a different audience. Traditionally, schools reserve learning about algebra for a later grade than learning about fractions. So, when extending a medium, MBD designers may find that their ELE addresses different learning goals and a different group of learners for whom those goals are important. Designing with a medium for learning necessitates focusing on the solution space (the medium), as the problem space (learning goals and learners) can change quite drastically. Trying to impose a certain learning goal or audience on a medium is futile if the medium does not afford it. So, MBD necessarily must be a process that starts in the solution space.

4.2 Example 2: Turtle(s)

In the previous case, we focused on two similar physical manipulatives that demonstrate that an extension to a medium can transform that medium's learning affordances drastically, to the point that new learning goals are addressed by the environment. In this example, we aim to demonstrate this effect again in a different setting—programming languages. We will describe Logo and StarLogo, show how the one extends the other, and how this drastically affects the learning goals of the two ELEs.

Logo is a widely distributed programming language designed for children (Papert, 1993b). With Logo's turtle-graphics, children can program a virtual turtle, shown as a triangle (or as a bitmap turtle in some versions of Logo), to move around the screen, thereby drawing lines and shapes (Papert, 1987). For example, when *FORWARD 100* (or *FD 100*) is executed, the turtle steps forward 100 units, leaving behind a straight line of 100 units in length. When *RIGHT 90* (or *RT 90*) is executed, the turtle turns 90 degrees to the right. Repeating this sequence four times results in a square with sides of 100 units (left part of Figure 5). Unlike previous programming languages' graphic systems, turtle graphics is not based on drawing lines from one coordinate point to another coordinate point. Instead, it is based on a body syntonic model—the programmer can imagine themselves in place of the turtle when trying to create a shape (i.e. "How would I move in a circle?"). In the case of the circle, it is easy to realize that all it takes is repeatedly going forward a bit and turning a bit (right part of Figure 5).

Because the turtle can make the same movements as the learner (go forward, go back, turn right, etc.), turtle graphics afford learners mapping their understanding of movement

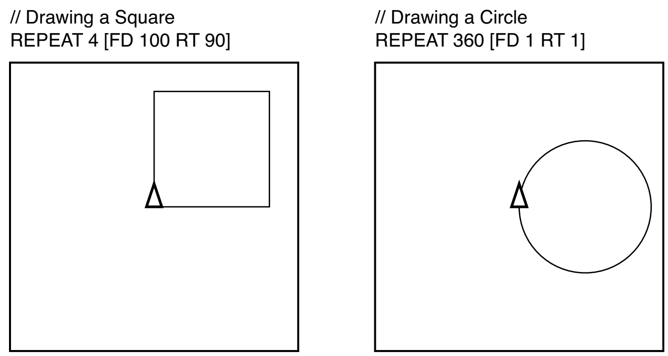

Figure 5: Using Logo to draw a square and a circle

to the virtual turtle. Because the virtual turtle can move precisely and leave a trail showing where it has been, turtle graphics afford drawing simple geometric shapes, such as squares and circles. Thus, by playing with turtle graphics, learners can explore geometry in a way that leverages their understanding of movement. Viewed from McLuhan's (1964) perspective that media extend man, Logo's turtle is a medium that extends man's legs. The turtle movement is similar to the movement that our legs afford us. As the turtle medium additionally affords moving precisely and keeping a useful record of that movement, it affords us understanding geometry better than simply moving with our legs.

In the previous case, we showed how extending a physical dimension (width) changed a medium. In this example, we show how extending quantity can change a medium. Instead of the learner programming one turtle, what happens when the learner is programming a massive number of turtles? StarLogo is a programming language that allows learners to do this (Resnick, 1994). As a programming language, StarLogo's syntax is nearly identical to Logo's. The main difference is that users program one turtle in Logo and program massive amounts of turtles in StarLogo. In addition, StarLogo turtles have better senses and their environment, a grid of patches, also has computational power (Resnick, 1996). So, for instance, a StarLogo turtle may pass on commands to the patch below it; the turtle senses the patch below it and can send a command to that patch, which can then, for instance, change one of its variables. When Resnick (StarLogo's designer) uses StarLogo, he is not using it to explore geometry, but to develop simulations of decentralized behavior, as displayed by slime mold, termite colonies, and traffic jams (Resnick, 1994).

Figure 6 shows several frames of such a simulation—an ant colony foraging for food. Initially, all of the ants are located in the anthill (the large mound in the center) and four mounds of food are placed at different distances from the anthill (Frame 1). When the simulation starts, the ants scurry out of their anthill. According to their programs, unless sensing pheromone nearby, the ants just move around randomly (Frame 2). At some point, some of the ants will come upon some food (located in the patch below) by chance. When this happens, their behavior alters. They pick up the food, decrementing the food variable in the

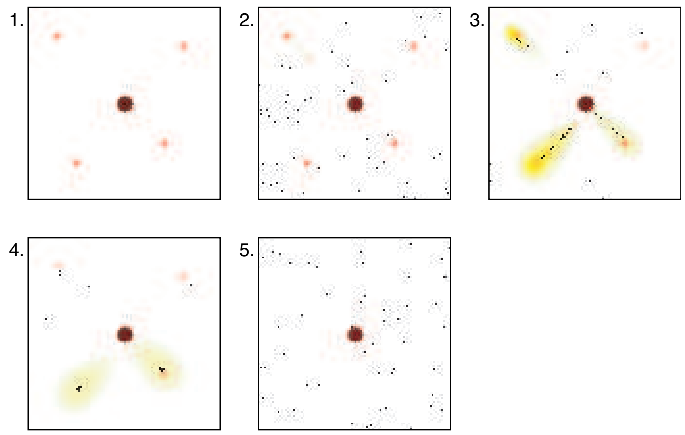

Figure 6: Frames from an ant-colony simulation in StarLogo

patch below, and take it back to the anthill, dropping pheromone to the patches below them along the way. The patches will slowly diffuse and dissipate this pheromone. When ants (who are not carrying food) realize that there is pheromone in their immediate proximity, they behave differently. They start moving in the direction of the strongest pheromone. At this stage, they will find food in that direction and help to enforce that pheromone trail by bringing the food back to the anthill. Strong pheromone trails will develop to the food, allowing most of the ants to become a productive member of one of these trails, bringing food back to the anthill and enforcing the pheromone trail (Frame 3). After a short while, the food at the end of these trails will have been exhausted. But, the ants still try to find food at the end of the trail, as the pheromone is still strongest there (Frame 4). Eventually, the pheromone is dissipated by the patches and the ants scatter, reverting to their earlier behavior (like Frame 2). New pheromone trails will develop (like Frame 3) and food there will be exhausted (like Frame 4). Eventually, all four food mounds will have been taken back to the anthill and the ant movement will simply be random (Frame 5). The simulation is over.

Though the ants in this simulation are efficient at finding food and bringing it back to the nest, they are not being commanded by a centralized force. There is no queen ant giving orders. Instead, this anthill is a decentralized, yet organized, system. All ants follow fairly simple procedures, based on their local information. Yet, the emergent behavior seems organized (particularly in Frame 3). Resnick (1996), in his studies with StarLogo, found that most people have a hard time attributing organized behavior to decentralized causes. They get stuck in a centralized mindset, mistakenly attributing emergent behavior to centralized causes. StarLogo provides a medium for learners to explore and even construct such decentralized systems (Resnick et al., 1996).

Though these two media (Logo's turtle-graphics and StarLogo) are similar morphologically (the one extends the other by increasing the quantity of turtles to program) and one was even developed from the other (Resnick, 1996), they are quite different in their affordances for learning. Logo's turtle-graphics focuses on geometry. StarLogo focuses on decentralized systems. Like fractions and algebra in the previous example, these different learning goals are appropriate for a different group of learners. So, this comparison gives a further example of how extending a medium (working in the solution space) can drastically affect the learning goals and audience addressed (the problem space).

In addition, it gives a great example of how starting in the solution space might have additional advantages to starting in the problem space. Papert argues that StarLogo is a clear example of the solution leading the problem (Resnick, 1994, foreword). Learning about decentralized systems is not something that you will see in school curricula. So, educational designers constrained to a certain problem space (addressing an important problem in a certain curriculum) would never have created StarLogo. Yet, decentralized systems are important. StarLogo offers a learning environment where these important concepts can be explored in ways that were not nearly as accessible to learners before its creation.

A problem with a design approach, like MBD, that starts in the solution space is that the learning environment designed may not address any important learning goals. While we acknowledge this as a real concern, we feel that the advantages of having a formalized process for creating an ELE outweigh this advantage of a design approach that starts in the problem space. Yet, as StarLogo demonstrates, an approach that starts in the solution space may actually have a corresponding advantage—the solution (the learning environment) could solve a problem (an important learning goal) that had not been acknowledged before then.

5 Using Medium-Based Design

The previous section detailed how extending media is a powerful design method; however, it did not show that this method was actually used in the design of these ELEs. The analysis was based on the product and not the process of design. One cannot deduce process from product (Goel & Pirolli, 1992). As such, we are not claiming that fraction sticks, algebra rectangles, Logo, or StarLogo were designed using MBD. As these learning environments were designed before MBD was articulated, the designers clearly did not design under the MBD name, even if their processes were similar.

In this section, we concern ourselves with the design process. We examine two learning environments, AudioExplorer and DigiQuilt, which were developed by the authors using MBD. Both are similar in scope, yet different in approach. Both were implemented in Squeak (Guzdial & Rose, 2002), a system purposefully engineered for creating these kinds of environments. Both are similar in complexity. Where they differ is that AudioExplorer is an inquiry tool and DigiQuilt is a constructionist medium; these are two large categories of ELEs (Hay & Barab, 2001). Comparing across these major categories should make the conclusions applicable to the design of a broad range of ELEs.

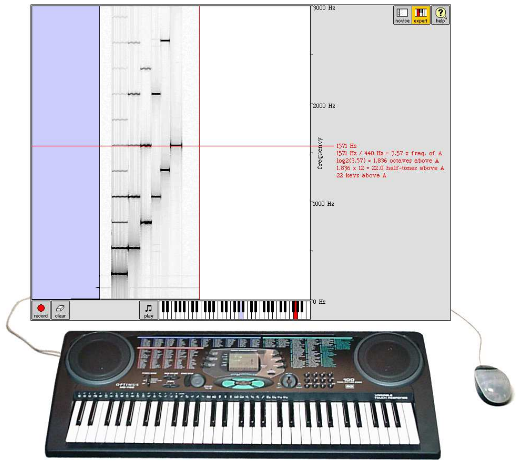

Figure 7: Using AudioExplorer to investigate the first six harmonics of a C note

5.1 AudioExplorer: an Inquiry Tool

AudioExplorer is a computer-based inquiry tool to explore the physics of sound by examining the frequency domain (Rick, 2002a). 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 sound, such as the harmonic sound that is essential to music. The learning system consists of a music keyboard transmitting sound input to a computer (Figure 7); the AudioExplorer software displays the signal on the screen, which can then be analyzed by the learners.

The idea for AudioExplorer came from a wish to explain why there are twelve half-tones in an octave. Given Rick's background in digital signal processing, he 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. Rick started playing around with Squeak's sound capabilities and various sound inputs. 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 adding 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 western 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 create an effective ELE. Personal connections are necessary; others would have to be able to engage the medium in a useful way. To test out how others could engage the system, Rick, inspired by reflection-in-action (Schön, 1987), conducted informal user testing. 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 demonstrated that only a little bit of appropriate guidance was necessary to allow users to engage the system.

Based on a suggestion from a colleague, the possibility for using the system to investigate the differences between instruments was researched and proved viable. In this way, AudioExplorer became a system that linked multiple representations of the sound input. 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. This shows how the technique of extending a medium works on a small scale. In novice mode, AudioExplorer is a medium to explore the differences between instruments. In expert mode, AudioExplorer is a medium to explore the mathematical workings of harmonic sound. By extending the novice AudioExplorer with analysis tools, it became a new medium with a new message.

By this time, the learning goals were clearly established. Based on Roschelle's work on dyads using an inquiry tool together (Roschelle, 1996), the learning situation became having two novices work together on an open-ended[3] laboratory assignment. Finally, an appropriate learning situation for using the ELE was found: a "Physics of Music" class at Georgia Tech. For formative evaluation, two groups used AudioExplorer; both groups achieved a good understanding of the learning goals (Rick, 2002a). Based on this, several interface changes were made to the AudioExplorer software to increase usability.

5.2 DigiQuilt: a Constructionist Medium

DigiQuilt is a computer-based construction kit for learning about math and art by designing patchwork quilt blocks (Lamberty & Kolodner, 2002). Increasing in size, DigiQuilt is made of 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 patches. The software offers learners 2-by-2, 3-by-3, or 4-by-4 patch quilt-blocks with a variety of grids that can be imposed on them, facilities for saving and loading designs, 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

[3] 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.

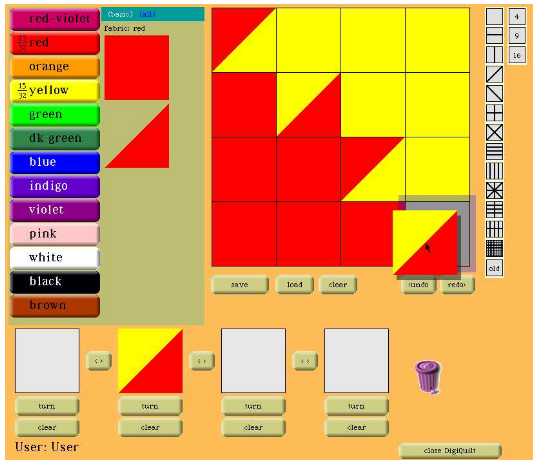

Figure 8: Using DigiQuilt to create a quilt block design (actual 3rd grader's design)

repeated or changed (Figure 8). 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 a context for discussions of the targeted concepts among the learners.

Designing DigiQuilt came from a desire to highlight the interesting math found in the world of patchwork quilt design. The designer, Lamberty, noticed that patchwork represented a potential medium to explore many mathematical ideas: fractions, symmetry, etc. Quilting could be an interesting interdisciplinary link for math, art, and possibly history. The choice to focus on math and art rather than history was strongly influenced by the fact that the math and art connections lie within the medium and can be learned through design. The history connections can be made in other ways by providing students with resource materials including storybooks and books featuring antique quilts. 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 to see what sorts of designs could be created and how to structure the activities. 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, 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.

This design decision highlights two important aspects of MBD. First, it demonstrates the importance of strictures. In DigiQuilt, the learner is constrained to rotating pieces by 90 degrees. Instead of being a burden, this stricture makes the learning goals more salient. Second, it demonstrates the power of the computer as a tool for realizing MBD. Compared to the paper prototypes, restricting rotation to only 90 degrees was easy to implement in software and feels much more natural to the learner. In MBD, the computer allows for the easy creation of powerful strictures and structures that make the learning goals more salient.

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 inspirational 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.

This design decision highlights another important aspect of designing learning environments: Design for learning is different than design for use. If the goal of DigiQuilt was quilt creation (a user goal), having different orientations of the same shape is useful; it saves the designer valuable time. But, the goal of DigiQuilt is to foster mathematical understanding through quilt creation (a learning goal). As such, having only one orientation for the same shape is useful; it makes the learner engage the learning goals.

For the first classroom trials of DigiQuilt, 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, that allowed the overlaying of various grids on top of the block (Figure 8 shows a grid with three vertical and three horizontal bars).

Challenges that involved equivalent fractions were difficult for students to understand. For example, when approaching the challenge, "create a quilt block that is $\frac{1}{2}$ yellow, $\frac{1}{4}$ red, and $\frac{2}{8}$ blue," students ran into several difficulties. Some students did not understand that the three fractions added up to 1 and would result in the whole quilt block being filled. Some students began by filling the quilt block with $\frac{1}{2}$ yellow, and then filled $\frac{1}{4}$ of the remaining space with red. Since this didn't leave 8 squares behind, some students simply 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 4-by-4 patch-grid: first just one heavy line to emphasize $\frac{1}{2}$, then another line to emphasize $\frac{1}{4}$, and finally enough lines to break the design into 8 equal parts so the students could finish the design with the $\frac{2}{8}$ 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 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 in the classroom. 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 message (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.

5.3 Product (ELE) Revisited

In the previous sections, we described AudioExplorer and DigiQuilt, two ELEs created using MBD. In this section, we aim to show how these environments meet the characteristics of ELEs. Thereby, we confirm that these environments are ELEs and provide concrete examples of the characteristics of ELEs in context.

An ELE is empty of content. AudioExplorer acts as a simple inquiry tool, such as a voltmeter or scale. Learners provide content, by playing on the keyboard, and then use AudioExplorer to analyze it. DigiQuilt acts as a constructionist medium. It is up to the learners to construct the content, by creating a digital quilt.

The interaction facilitated by ELEs is open-ended. In both AudioExplorer and DigiQuilt, the environment itself is open-ended (learners decide how they use the environment), but, in use, the learner control is more guided (i.e. not unrestricted). In AudioExplorer use, a laboratory assignment suggests what is worth investigating. In DigiQuilt use, learners are given specific challenges, such as "cover $\frac{1}{3}$ of the quilt block with one color and $\frac{2}{3}$ with another color." In both cases, the environment is open-ended and the challenges focus that open-ended inquiry to better address learning goals. Both of their use is still open-ended, as learners can meaningfully approach these challenges in different ways.

An ELE is structurally simplistic. AudioExplorer is simple; it focuses on one input—musical sound coming from a keyboard. It harnesses the computational power of the computer to transform that input into multiple representations. Each of those representations allows learners to focus on a specific feature of the musical sound. DigiQuilt is simple; it focuses on the construction of a quilt block with a limited amount of pieces. Those pieces can only be placed into the quilt block in a fairly constrained way. The computational power of the computer enables DigiQuilt to create structures and strictures that go beyond the capabilities of a physical construction kit.

An ELE offers concrete connections to the important concepts. AudioExplorer extends the piano, a medium that has concrete connections to western music. It extends the piano to display the frequency domain, which has concrete connections to how we perceive sound. The learner is able to connect the concrete (musical sound) to the concepts (structure of harmonics). As such, they can explore how and why western music works (e.g. why does a chord sound good?). DigiQuilt extends patchwork quilting to focus the creation process on mathematical concepts (fractions, symmetry, etc.). When a learner adds to a quilt block, the fraction of the quilt block that is covered by a color is displayed next to that color (see Figure 8). So, the learner is able to connect the concrete (the fractions of the quilt block) to the important concepts (mathematical fractions).

An effective ELE has personal connections. As the example at the beginning of this article demonstrates, physics-of-music students are able to leverage their previous knowledge of music to better understand what AudioExplorer is displaying. Music is important to our culture; as such, there is an intrinsic interest in trying to understand it. AudioExplorer leverages that interest to motivate learners. Art, such as patchwork quilting, also has a strong cultural meaning. DigiQuilt leverages that interest to motivate learners. In addition, they are creating a personally meaningful artifact (a digital quilt), which can be highly motivating (Papert, 1991).

An effective ELE has epistemological connections. AudioExplorer connects to the harmonic properties of music. DigiQuilt connects to mathematical and artistic concepts. For both of these environments, the concepts addressed are relevant to their audiences. For physics-of-music students, understanding why music works is important. For fourth graders, learning about fractions and symmetry is important.

5.4 Process (MBD) Revisited

The previous section was concerned with product—how AudioExplorer and DigiQuilt reflect the characteristics of ELEs. This section is concerned with process—how the design of AudioExplorer and DigiQuilt reflect the phases of MBD. We address this to confirm that these environments were created using MBD and to give concrete examples of the phases of MBD in action.

Begin by choosing a medium you know well, care about, and feel has learning potential. 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 long before the design process started. For a soft-style method of design, it is advantageous to have an affinity (or closeness) to the object to be manipulated. Through these ELEs, the designers were able to share their enthusiasm for the medium with others.

Explore the medium to understand its affordances for promoting learning. If the strength of the hard-style problem-based approach is knowledge of the problem space, the strength of the MBD solution-based approach is knowledge of the solution space (what does the medium afford). Both design methods involve reflective exploration of a search space and are therefore not arbitrary. 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. 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.

Extend the medium to change those affordances. It is not coincidental that both DigiQuilt and AudioExplorer have different user modes. The different modes accentuate (or extend) 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.

Transition from the solution (the medium) to the problem (a clear message). AudioExplorer design began by investigating the affordances of the frequency domain. AudioExplorer evolved into a medium to understand how and why music worked. Finally, an appropriate audience was found. The solution (AudioExplorer) addresses an important problem (how and why music works) for that audience (physics-of-music students). DigiQuilt started off investigating the affordances of patchwork quilting. It evolved into a medium to connect mathematical concepts to art construction. Finally, an appropriate audience was found. The solution (DigiQuilt) addresses important problems (fraction understanding) for that audience (fourth graders).

Though neither design started off with an intended audience or clear problem that it was trying to address, both ended up addressing important problems for a real audience of learners. Though neither design started off from specific user needs, both design processes were user-based and met both the usability and learning goal needs of their audience.

6 Assessing Medium-Based Design

In the previous section, we detailed two learning environments, AudioExplorer and DigiQuilt, created using MBD. We hope to thereby provide a rich description of how and why MBD allows for the creation of ELEs. Because these environments were designed by us, the authors, the conclusions are limited. At best, we can conclude that MBD can be effectively used by its originators to create ELEs. To be truly effective, a design method needs to be useful to others as well. It also needs to be better in some way to alternative methods; otherwise, there is no advantage to using it.

In this section, we address these issues empirically. We seek to show that others can use MBD in the creation of ELEs. In particular, we look to confirm our hypothesis that MBD is more suited towards the creation of ELEs than a hard-style design (HSD). This led us to focus on how the products of MBD and HSD differ. If the hypothesis held, the products of MBD could better be characterized as ELEs. To address this topic, we conducted a comparative study of MBD and HSD. In this section, we detail this study. First, we describe how the study was conducted. Then, we examine the results to test our hypothesis. Finally, we address the challenges of studying design methods and confront some of the limitations of our study.

6.1 The Study Setup

To test our hypothesis we carried out a study in a computer science class on educational technology. In that class, students had to work in groups on a large (both in terms of time commitment and point value) design project. The class was split up into design groups (2-3 members per group). Six of the groups were given a MBD guideline and the other six were given a HSD guideline to follow. These guidelines scaffolded each phase of the design process. The groups went through four phases of the design. The phases in the MBD guideline roughly approximated the phases of MBD: 1) pick an interesting medium; 2) build the prototype to explore the problem space; 3) trial the prototype in user testing; 4) get feedback from classmates and finish the design. The phases in the HSD guideline roughly correspond to: 1) pick an important problem; 2) explore the problem space through user interviews; 3) prototype the design; 4) get feedback from classmates and finish the design. Due to the limitations of the class, none of the groups actually fully realized their design, though all had to at least create a prototype. As we are trying to determine the effectiveness of the design method, this may actually be beneficial: These prototypes may be more representative of the design methods (MBD and HSD) than a finished learning environment, as they come early in the process when the design is still largely governed by the design method and less by the particulars of the learning context.

After their projects were completed, students were given a survey so we could better understand their design process and products. The advantage of having students reflect on their own designs are twofold. First, students are not invested in MBD and are thus unbiased towards certain conclusions. Second, the students were the designers, so they have a familiarity with their design (particularly, their process) that an outsider could not have. To analyze the data, the responses for each group on a 1-5 Likert scale were averaged and compared across the study condition. Two groups, one from each condition, were removed from the analysis; these groups failed to follow their respective design guidelines closely, so both their process and product were not representative of either design process. This analysis allows us to explore our hypothesis that MBD is more successful than HSD in the creation of ELEs. The results suggest our hypothesis has merit.

6.2 Results

One of the defining properties of an ELE is that the teacher transitions from being the "sage on the stage" to being the "guide on the side." In other words, the teacher becomes a guide to engaging the learning environment, rather than the transmitter of information. The survey data suggests that this transition occurs more in MBD groups (see Table 1).[4] Both MBD and

[4]Because of the small sample size (five versus five), statistical testing does not make sense for this analysis. Rather, this is a suggestive analysis based on trends in the descriptive statistics.

Question	MBD	HSD
The teacher plays a large / important role in my group's design.	3.73	3.73
In my group's design, learners learned from (either human or electronic) experts or teachers.	2.83	4.37

Table 1: *Sage on the Stage vs. Guide on the Side*, where 1 is strongly disagree and 5 is strongly agree

Question	MBD	HSD
My group's design closely matches cognitive apprenticeship.	2.83	3.40
My group's design closely matches inquiry-based learning, such as Learning by Design and Problem-based Learning.	3.47	3.23
My group's design closely matches constructionism.	3.80	3.20
Compared to other groups, my group's design is more constructivist (the learners construct their own understanding, as opposed to memorizing material).	3.83	3.43

Table 2: *Alignment with Learning Theories*, where 1 is strongly disagree and 5 is strongly agree

HSD groups agreed that the teacher plays an important role in their design. Yet, when asked whether learners learned from experts or teachers, the two groups diverged. HSD groups felt more strongly that learners learned from experts or teachers in their designs. For MBD groups, the teacher was still considered an important part of a learning environment, but the learners were not learning as much directly from the teacher. This suggests that the teacher's role is more like a "guide on the side."

The survey also suggests that the designs created with MBD align better with learning approaches that are in-line with ELEs, such as constructionism. This prediction proved true to various degrees (see Table 2). Constructionism, inquiry-based learning and cognitive apprenticeship were covered extensively in class, so students were aware of what alignment with those theories meant.[5] For MBD groups, the most alignment was with constructionism and the least alignment was with cognitive apprenticeship; for HSD groups, the alignment results were reversed. So, the results suggest that MBD may be a comparatively useful method for designing constructionist environments. The survey also indicates that MBD groups considered their systems to be more constructivist (Table 2).

Finally, how learners learned was compared. We were interested in how students are

[5]In the actual survey, intelligent tutoring systems were included as a fourth category for students to align with. Since ITSs were only briefly mention in class, it is likely students had a hard time responding to that question accurately. As such, it was excluded from this analysis.

Category	Difference
...from (either human or electronic) experts or teachers.	1.03 (HSD > MBD)
...from their peers / fellow learners.	0.03 (HSD > MBD)
...from external materials, such as reading.	0.61 (HSD < MBD)
...by playing around / trying things out.	0.44 (HSD < MBD)

Table 3: *Learners Learned...*, based on a 1 (strongly disagree) and 5 (strongly agree) scale

learning in these environments. Are they learning from experts or teachers? Are they learning from their peers? Are they learning from external materials? Are they learning from playing around (exploring)? In particular, we are interested in how answers to these questions compared to each other within groups. To get at this, we normalized the data around the average answer for each group. In that way, a group was treated the same whether they were consistently in agreement that learners learned from these sources or consistently in disagreement that learners learned from these sources. What counted was how one answer compared to another answer within that group. The prediction was that MBD designs would get more of their learning potential from playing around and less from experts or teachers. Again, this prediction proved true to various degrees (see Table 3). HSD groups were more confident that their learners learned from experts and teachers. In contrast, MBD groups were more confident that their learners learned from external materials or by playing around.

6.3 Challenges and Limitations

While we are encouraged by these results, there are a number of limitations to our findings due to the difficulty of studying design methods. Comparing design methods is always challenging. Comparing design methods in the complex field of learning environment design is even more difficult for a number of reasons:

1. *Designers must have an adequate background.* To engage in the reflection-in-action process (Schön, 1987), designers will have to be both skilled in education and computer science. Only someone familiar with learning theory can reflect properly on his or her design. Only someone capable of programming can properly act on that reflection. There are few who meet both requirements. As such, there is a small pool from which to recruit designers to take part in such a study.

2. *Designing an effective learning environment involves substantial time and effort.* At a minimum, designers must plan their design, execute it, and refine it based on use. Often, further design steps are necessary. Finally, to demonstrate its effectiveness, the learning value of the design must be evaluated; this alone is often a challenging task.

3. *Many factors influence the success of a design project.* Some designers are more experienced or gifted than others. Some ideas simply bear better fruit. Some contexts of use are more congenial to learning outcomes than others. The number of factors involved make it difficult to correlate any success (or failure) to the choice of a design method.

4. *Different learning environments are difficult to compare.* How do you compare learning environments that address different learning goals? How does a ten percent pre-test / post-test gain in factoring Algebraic equations compare to a better understanding of how an ant colony secures food? Unless the learning environments address the same learning goals they are impossible to compare directly. Even when they address the same learning goals, environments are difficult to compare.

These reasons make it difficult to study this domain. Given our limited means and the difficulty of the task, we face several challenges to the validity of our study. First, because it is difficult to recruit designers, we only have ten (five versus five) data points. Consequently, there is no way to achieve statistical significance, a common criteria for evaluating the validity of a study. However, we are encouraged to find that the results support several of our hypotheses. Second, due to time and effort considerations, the designs were carried out by novices. It is questionable whether their experiences reflect those of expert designers. Third, all designs were evaluated by novices. Whether their judgment is accurate is questionable. For instance, survey data on personal and epistemological connections had to be thrown out, because it was clear from the final exam that many students did not properly understand these concepts. Fourth, the designers did not fully realize their designs; they only created paper designs or (at best) prototypes. It is questionable whether these limited designs reflect the ultimate product of the design process. Fifth, the results are situated in our context of study (Georgia Tech students, Rick as the instructor of the course, the specific implementations of MBD and HSD, etc.). As within any such situated study, it is questionable whether the results transfer to a different situation.

We hope that it is clear from this discussion that comparing design methods in this field is challenging. Inevitably, it involves limitations. Even if we had outrageous means and could study many expert designers realizing full designs, we would still face problems. First, we would have to account for differences in experience and effort—something that is largely controlled for in our sample of novices. Second, it would be difficult to attribute success or failure to the design method rather than the particulars of the learning context. Third, it would still be difficult to impossible to directly compare the effectiveness of the different environments.

Comparing design methods for creating learning environments is inherently challenging. Yet, we should not ignore an area of study just because we are unable to obtain the kind of evidence standard in other domains (Yin, 2003). Otherwise, we are like the man who prefers to search for his keys under the streetlight where visibility is highest, rather than the dark alley where he lost them. We will never find the key. In this study, we admit to searching in the dark alley, where evidence is hard to come by. Yet, we are encouraged by our results.

7 Discussion and Conclusions

In this article, we introduce a new approach for creating learning environments, MBD. We detailed both the goal of creating ELEs and the MBD approach for reaching that goal. Our hope is that the reader will have a better understanding of ELEs and why MBD is a useful method for creating ELEs. While we value ELEs and exploratory learning in general, we do not argue that all learning environments should be ELEs; there are many useful ones which are not. We also do not argue that MBD is the only approach that enables designers to create ELEs; designers have created ELEs before we articulated MBD. Yet, we do feel that MBD is a particularly useful method for creating ELEs. At a minimum, it has worked for us; furthermore, our study suggests it can work for others.

7.1 MBD and ELEs: Soft-Style Design, Soft-Style Learning

We believe that in articulating and grounding a soft style of design, we can provide an alternative to designers. As soft-style designers, we have often had our design process maligned: “Your process is arbitrary and that your design product is useful is largely *despite* the process.” With this work, we aim to combat that attitude. Turkle and Papert (1991) revalued the concrete by showing that a soft style was an acceptable, useful learning style. Here, we revalue the concrete by showing that a soft style of learning environment design too can be grounded in theory, have common properties (i.e. the process is not arbitrary), and be successful *because* of the process. It is probably not incidental that our soft-style design method (MBD) is useful in creating environments (ELEs) that allow for a soft-style learning process (learning by exploring concrete environments).

7.2 Limits: Who should use MBD?

MBD is by no means a panacea for the problems of learning environment design. In an early presentation of MBD, one colleague pointed out that MBD takes time and creativity in addition to being counter to a suggestion often offered teachers: “Start with learning goals and develop activities that help students achieve those goals.” We agree with that assessment. While MBD may be a great method for us, we realize it may not be appropriate for others.

One reason MBD works for us is that we, as computer scientists, are able to harness the power of the computer to create a new medium. Practically, this requires programming. Programming applications that learners can use is a challenging, time-consuming task. It is doubtful that an average teacher has either the time or the programming ability to use MBD. Even if a teacher had the time and ability to use MBD, they face further challenges. Teachers are responsible for helping their students meet particular learning goals. In MBD, the problem and thereby audience addressed by the product of the design process is not known from the beginning of the design process. So, even if our "überteacher" created an ELE using MBD, in the end it might not be useful for his or her students. As such, we do not feel that MBD is an appropriate design method for most teachers.

While it is probably impractical for teachers to design using MBD, teachers are crucial to the use of ELEs in the classroom and can play a useful role in MBD. A good teacher can adapt an ELE to suit the learning needs of their students. As Papert recalls of his experience with Logo, "I have been extraordinarily gratified to see teachers using Logo as a painter uses paint, that is, as a medium for creative work, in this case for the creation or enhancement of learning environments" (Papert, 1993b, p. xiv). A good MBD designer often needs to work closely with a teacher (particularly in phase 4); the teacher is in a good position to evaluate the usefulness of the ELE for his or her students for meeting their specific learning goals.

In our experience, in learning environment design, computer programmers are often relegated to simply implementing the software ideas of others. That approach is incompatible with our notion of MBD. In MBD, programmers must play a primary role in creating ELEs. Those programmers must have a fairly good understanding of learning theory and be able to work with other educators (curriculum designers, teachers, etc.) to realize their designs. This is far from a trivial task. We are fortunate in that we had the flexibility and enough expertise to carry out MBD. We hope that by pointing out the benefits of our approach that others may come to value those opportunities and make them available to others.

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