

SmartTiles: Designing Interactive “Room-Sized” Artifacts for Educational Computing¹

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Abstract

Historically, the notion of design for educational computing has assumed that the “computer” in question is a desktop box. In this paper we describe a genre of educational computing in which the artifacts designed are “room-sized:” moderate-to-large-scale objects or furnishings with which children can interact in powerful or interesting ways. We describe a working prototype of one such system—SmartTiles, a system of large-scale programmable “tiles” that can endow surfaces such as walls with interesting, child-controlled dynamical behaviors. While SmartTiles is still at a relatively early stage of design—and has yet to be formally tested with children—it nonetheless illustrates a potentially important and novel genre of design for children’s environments. We contrast the notion of “room-sized educational artifacts” with related research directions in interface design and educational computing, and we discuss what we believe to be central issues in the design of such artifacts.

Keywords: [SmartTiles](#), [educational computing](#)

Introduction

Historically, the term "educational computing" has meant, more or less, "software development for desktop machines." Within this desktop-oriented tradition, the great majority of educational computing artifacts can be classified within one of a dozen or so prominent genres (e.g., tutoring systems, simulation tools, design applications, games, programming languages). Despite the wide range in pedagogical philosophy suggested by these genres, they all share a basic, unshakeable assumption of what "the computer" is—namely, a desktop box equipped with screen, keyboard and (more recently) Internet connection. While this tradition of design has been (and continues to be) extremely productive, creating marvelous artifacts for children and adults, it is nonetheless inevitably constrained by its assumptions of the essential nature of computational media. Computers needn't be boxes on desks, and the advent of a variety of novel, accessible technologies that challenge, complement, or extend this traditional image portends fascinating new possibilities for the design of educational computing artifacts.

In many important respects, this re-examination of the field is already under way, with researchers exploring, for example, the possibilities of handheld and wearable devices (cf. Bannasch 2001). This paper presents another example—a working prototype—of an innovative style of educational computing, one in which computational media are designed at "room size," as a kind of interactive medium-to-large-scale furnishing for children's spaces. *SmartTiles* is a system of individually programmable tiles that can be arranged onto surfaces, thereby endowing those surfaces with interesting, complex, and customizable behaviors. Although *SmartTiles* is merely a prototype, it illustrates the possibilities for creating large-scale interactive artifacts that can engage children away from the computer screen.

In the remainder of this section, we discuss the ideas behind room-sized artifacts for educational computing, and we contrast this idea with several related but distinct notions such as pervasive computing and the design of "intelligent" interactive toys. The second section describes *SmartTiles* in a bit more detail, outlining implementation of the project. The third section is a wider-ranging discussion on the subject of technological enhancement of children's learning and play environments; here, we draw on sources from a wide variety of disciplines ranging from educational technology to the architecture of children's spaces. The fourth and final section discusses both related research and possible directions for future work on room-sized educational artifacts.

The Room as the "Grain Size" for Educational Computing Artifacts

There are, or should be, a variety of "grain sizes," or scales, at which to think about design for educational computing. Historically, the desktop (and the television-sized screen) has been the default grain size of design; alternative grain sizes might include those associated with handheld devices or toys. A fundamental argument of this paper is that the room constitutes a particularly productive grain size for thinking about children's computing. By considering room-sized artifacts, we might re-imagine the design of (among many other things) children's mobiles, windows, window curtains, wallpaper, posters, carpets, shelves, and so forth—endowing one or another of these objects with interesting, beautiful, informative, or creativity-

enhancing affordances generally associated with interactive computer programs. Children's rooms or classrooms might exhibit no more than one or two such examples of "interactive furnishings;" otherwise the environment might be too busy or jarring. Nonetheless, exploring the possibility of such room-sized interactive artifacts for children seems to be a particularly exciting direction for research.

The traditional "screen-sized" scale for educational computing tends to enforce a kind of segregation between computational media and everything else within the child's environment: in effect, the screen becomes the sole location where a certain kind of thinking (or creating) is permitted to take place. We argue that this disconnect between computational activities (in front of a desktop box) and noncomputational activities (everywhere else) does a disservice to both classes of activities. It implies that computational activities are limited in the sorts of physical or sensory experience that they can provide or enhance; at the same time, it implies that other artifacts cannot exhibit complex or interactive behaviors.

Consider the first part of the previous sentence: limiting educational computing to the screen constrains the possibilities for computing itself. Part of this limitation is physical: the range of physical activity that accompanies most desktop systems is highly constrained. One cannot have the experience of, for instance, standing inside, or walking along, or climbing upon, or wrapping oneself in, a desktop computing artifact. Screen-based artifacts, however rich in color or sound, are surprisingly impoverished kinesthetically, and as such, speak to only a limited range of children's educational experiences.

Still another aspect of this limitation is social: desktop machines are limited in social affordances just as they are in sensory affordances. Here, the fan of the desktop device will leap to its defense: aren't computers leading to new social communities? Aren't they the media through which children participate in chat groups, multi-user games, and the like? Of course, these are wonderful and important social innovations; but considering the range of children's experiences, such desktop activities are still oddly constrained. Children do not have the experience of, for instance, forming a circle around a computer; or walking in a line along a computer; or placing their hands, along with the hands of all their friends, at different positions a computer; or draping a computer over themselves and a group of friends. In these respects, thinking of computing at the grain of the room permits us to imagine moderate-to-large-scale interactive artifacts that expand the traditional notions of what "computing" can look like.

Or consider the second implication noted above: that limiting educational computing to the screen constrains the possibilities of children's spaces. One might imagine mobiles whose behavior can be altered or controlled by children; or window displays that behave in interesting, child-programmed ways when the sun catches the window at a certain angle; or windowsills that alert the room's occupant to the presence of an interesting bird or insect; or wallpaper that responds to touch in interesting, customizable ways. These may be (for the time being) somewhat fanciful thought experiments, but they suggest the possibilities of reconsidering children's spaces by thinking of computational media at the grain size of the room—

whether the “room” in question is a classroom, bedroom, den, playroom, or museum lobby—and making those spaces more interactive or playful or idiosyncratic.

We argue that a productive way forward for the field of educational technology is to look to children’s rooms for sources of inspiration.²

Room-Sized Artifacts and Related Notions in Educational Computing

The preceding paragraphs introduced the basic motivation behind the design of room-sized educational artifacts. The following section will describe a working prototype of one such computational artifact, SmartTiles. Before going into more detail on that prototype, however, it is worthwhile to draw several important contrasts between the ideas behind it and those underlying some related but distinct lines of research in user interface design and children’s computing.

Pervasive/Ubiquitous Computing

Many of the artifacts imagined in the previous paragraphs suggest an integration of computational and physical media, and would likely be designed by embedding small computers within physical objects. Our SmartTiles prototype presented in the next section is designed in just this way. In this sense, our ideas could be seen as representative of a larger ongoing research effort in “pervasive” or “ubiquitous” computing; although these are broad terms, they typically refer to the design of systems in which small embedded computers are strategically placed within physical objects (or environments) to make them more responsive, adaptive, personalized, or (broadly speaking) “intelligent.”

Clearly, our own interests overlap a great deal with those of pervasive-computing researchers but there are differences in style and motivation between most pervasive-computing examples and the types of systems that we envision. Generally, the rhetoric behind pervasive computing stresses notions such as invisibility, “transparency,” ease of use, and so forth. While these terms are a bit informal, they collectively identify a set of design interests. An archetypal pervasive-computing project is one in which an object or environment is made responsive or adaptive to a user’s needs, relieving the user of tedium, effort, or discomfort, and doing so without any need for the user’s active effort or participation. Pervasive-computing artifacts are intended to work smoothly, autonomously, and quite possibly outside the user’s conscious awareness.

While we do not object to this vision in the abstract, it differs strongly from the motivation behind room-sized educational artifacts. The design philosophy behind artifacts such as SmartTiles is that they should *not* be invisible or transparent, but should rather be part of children’s conscious understanding of their environment. Perhaps an analogy with musical instruments is appropriate: a clarinet, for example, is not intended to be transparent, but highly controllable; it should not relieve tedium, but should be a medium of expression; it should not work like magic, but should invite understanding and mastery; it should not save time, but should have purpose. In the same vein, we see SmartTiles and similar artifacts as expressive media to enrich children’s spaces and environments, rather than as

technological means of relieving some putative sense of discomfort. In this sense, room-sized educational artifacts may be seen as diverging, somewhat, from the traditional concerns of pervasive computing research.³

“Smart” Toys

Some of the themes mentioned in the previous paragraph can likewise be applied to a contrast between systems such as SmartTiles and the remarkable, blossoming menagerie of “smart” toys. Again, this term is rather general, but tends to connote a class of children’s artifacts in which embedded computation is used to convey an impression of autonomous intelligence.⁴ A toy of this kind is typically designed to work “like magic,” and its apparent intelligence is manifested in the provocative complexity of its responses to the user’s actions.

While this is an extremely interesting and fertile area of design for children, it does contrast with the ideal of *child-controlled* artifacts that motivates this paper. Indeed, we feel a certain ominous sense of discomfort about toys that work “like magic:” they can be seen as miniaturized exemplars of a widespread approach to engineering that deliberately removes users from an understanding of design. A child who views her toys as magical is, in our view, just a short step removed from an adult who has no idea—who is not *supposed* to have any idea—what happens when a room’s light switch is flicked on. SmartTiles and other systems of this sort should, we believe, be capable of complex behavior—but that behavior should be understandable, explainable, and controllable by the child/user. For a system such as SmartTiles, this implies that children should be able to explain, truthfully (if non-technically), the rules that govern the operation of the system; and they should view those rules as the means by which they can control the artifact in the same spirit as a construction kit or musical instrument. At the risk of putting the point too aphoristically, child-controlled artifacts should evoke a sense of mastery, not mystery.

Digital Manipulatives, Participatory Simulations, and Handheld Classroom Devices

The line of work that is closest in spirit to our own is that of Resnick and his colleagues in their pursuit of “digital manipulatives” (Resnick et al. 1998). Traditionally, mathematical manipulatives are physical objects that serve as tangible illustrations of profound mathematical ideas (e.g., sets of wooden rods represent the concept of natural numbers, clock faces introduce ideas of modular arithmetic, and so forth). The notion behind Resnick’s artifacts is that they are extensions of this pedagogical tradition into the realm of digital technology. By giving mathematical manipulatives computationally-controlled behaviors, one can make an older tradition of educational objects more interactive; even further, one can create “manipulatives” appropriate to new and interesting mathematical content (such as the behavior of complex multi-part systems).

The SmartTiles project may likewise be seen as a “digital manipulative” in the sense that it permits physical exploration of mathematical ideas that a previous generation of manipulatives could not represent. However, the difference between our work and that of Resnick’s group is in assumptions of scale. The term

"manipulative" implies by its very etymology a focus on small-scale, hands-on educational artifacts. While this is a marvelously rich and important tradition, the source of metaphors for SmartTiles and the like is more likely to be found in the design of children's environments and playspaces.

This difference also provides a contrast between room-sized artifacts and other educational work in "participatory simulations" (Colella 2000) and projects that involve the use of handheld or portable technologies. The focus of SmartTiles and other such artifacts is, in contrast, on the way that they alter or redefine the interior spaces through which children move. Room-sized artifacts are closer in spirit, then, to furnishings, rather than to handheld artifacts.

Smart Tiles

The previous section described the basic principles behind room-sized educational artifacts, and contrasted these ideas with several other recent research areas in interface design and educational computing. In this section of the paper, we describe an operational (though still experimental) example of a room-sized educational artifact. It should be noted at the outset that our system is still a work-in-progress; the first pilot tests of the system with children are planned for later in 2005.⁵

Figure 1. A four-by-four array of SmartTiles



SmartTiles are individually-programmable tiles that can be combined into arrays to create complex dynamic displays. That phrase "individually-programmable" is crucial: each SmartTile contains its own separate computer, and each tile may thus be customized and reprogrammed by its user. Perhaps the most direct way of explaining the SmartTiles system is to refer the reader to Figure 1, which shows a four-by-four array of the tiles. Each of the 16 lights visible in the figure is associated with its own individual computer, and each tile (or computer, or light,

depending on how one wishes to think of it) can communicate with its immediate neighbors in the grid.⁶

The SmartTiles system represents a particular kind of computer model well-known in computer science: a *cellular automaton*. A fuller description of cellular automata is given in [Appendix A](#) to this paper; for the purposes of this discussion, we merely note here that cellular automata are capable of exhibiting beautiful and fascinating patterns of moving light and color, while likewise illustrating profound mathematical and scientific concepts. The SmartTiles system is, moreover, an *interactive* cellular automaton: each of the lights in Figure 1 can have its state (“lit” or “unlit”) changed by a direct press on the surface. Thus, a running SmartTiles system has patterns of light that are dictated by the computers in each tile, but can also be directly changed by user input.

Again, Appendix A provides more detail; the key points to note for the present are that SmartTiles are

- a. *Programmable*: the user can change or customize the program that sits inside each individual tile;
- b. *Extensible*: one can imagine collections of tiles covering large areas such as walls within a room;
- c. *Interactive*: users can affect via touch the patterns of lights that the tiles produce.

Room-Sized Educational Computing: The Central Issues

Some of the most pointed issues involved in creating room-sized educational artifacts are technological, rather than educational or social, in nature. For example, creating artifacts that can be programmed by children introduces the historically contentious issues of the appropriateness and utility of creating powerful programming environments for children. We leave discussion of these sorts of issues to [Appendix B](#) at the end of this paper.

Educational/Cognitive Issues

What sort of role might room-sized artifacts play in educational practice? Why should educators, or developmental cognitive scientists, have any interest in the development or assessment of such artifacts?

Our belief is that artifacts of this sort represent a type of design consistent with the broader tradition of “hands-on” education—or, more accurately, with the tradition of education that seeks to integrate conceptual development and sensory experience. Mathematical manipulatives, mentioned earlier, represent one corner of this larger design space, as they link abstract ideas (such as numbers, or modular arithmetic) to concrete objects that form the basis of visual or kinesthetic imagery (such as number rods or clock dials). The rationale behind manipulatives is that the abstract ideas of mathematics (as well as scientific theorizing in general) have their origins in physical and sensory experience.

This general rationale behind the use of physical objects as the basis for abstract reasoning may be traced back at least to the writing of Piaget (1972). While there are many debates over the proper educational use of manipulatives (cf. Ball 1992; Chao, Stigler and Woodward 2000), there seems to be general agreement that physical objects do play a central, formative role in mathematical and scientific reasoning. One particularly elaborate theory of mathematical reasoning, described at length in Lakoff and Núñez (2000), discusses the role of highly structured metaphors in mathematicians’ thinking. These metaphors are themselves based upon bodily and sensory experience. For instance, the Arithmetic is Object Collection metaphor arises naturally in our brains as a result of regularly using innate neural arithmetic while interacting with small collections of objects” (Lakoff and Núñez 2000, p. 60).

We believe that there is no particular reason to expect that educational sensory experiences need be restricted to small-scale “hand-sized” objects, although clearly these objects are of tremendous importance. Sensory experience comes through a variety of channels and at a variety of scales; physical objects can be held, but they can also be inhabited, ridden on, rolled upon, and so forth. The presence of larger, room-sized objects (such as a set of SmartTiles) is simply, in our view, an extension of the philosophy of “hands-on” education and manipulative design to larger muscular movements and more varied kinesthetic activity.

There are other possible cognitive affordances of these larger-scale objects. For example, many smaller-scale educational artifacts (such as number rods) are relatively limited aesthetically: they may act as cognitive scaffolds, but they are not the sorts of objects that children might pick up and reflect upon in their more idle moments. They are typically employed for a set amount of time (e.g., during a mathematics lesson), after which time they are put away and hidden from view. In contrast, room-sized educational artifacts could have a bit of the quality of personalized museum exhibits, particularly if they are present in a child’s home or classroom. The objects simply would become part of the environment, sometimes the focus of attention and sometimes not; they are not specifically created for “lesson time” but are instead likely to receive attention in an occasional and relaxed way, at odd moments of the day, much like wallpaper or a mobile. Moreover, these objects can be aesthetically compelling; a well-designed room-sized artifact should be a pleasure to look at and reflect upon. In these respects, room-sized artifacts can supply something to the educational mix that many other physical educational artifacts do not.

Social Issues

We anticipate that, over time, as robust working examples of room-sized artifacts are developed, educational designers will increasingly weave together a focus on cognitive development with social, anthropological, and architectural considerations. A designer of a room-sized artifact, after all, must consider questions of educational design: *what sorts of ideas and subject matter are embedded in these artifacts? How do children encounter and reflect upon those ideas? What additional materials might we provide to enhance the educational role of these artifacts?* At the same time, the designer must also consider more

architectural issues: *how will children move around in front of (or within, or on top of) this artifact? How will groups of children interact with it? How will this artifact interact with other elements of the setting?*

Much of the literature on children's settings and environments focuses on issues that are relatively new to the field of educational computing. For example, Gerber (2000) discusses research in such areas as environmental perception, environmental cognition, and environmental behavior and attitudes. He concludes,

The recognition that active doing and experiencing can be vital orients the curriculum away from transmissive experience to a more transactional one, especially when it is situated in real-world contexts (p. 36).

Robertson (2000) adopts a more psychological viewpoint, discussing the ways in which environments contribute to the development of a sense of identity in children:

Looking back as an adult requires a reconstruction of the place of childhood memory from which the building of 'self' can be understood. Places hold memories which go well beyond being sources of belonging and security.... They give us a unique signature, if you like, that distinguishes us from all other people (Robertson 2000, p. 131).

Such considerations are hardly arcane, but they are rarely discussed in the context of educational computing. As room-sized (and perhaps even larger) artifacts are developed, however, we must begin to think of the role interactive technologies might play in children's environments: what are the benefits and disadvantages of weaving computational media into notions such as "hiding spaces," backyards, private areas of the house, and so forth? Would these technologies intensify or dilute the sorts of identity-building role of the environment that Robertson alludes to?

Consider, for instance, the way in which a room-sized artifact, such as a SmartTiles wall display, could act as a background for conversation and discussion. The display, in this scenario, could serve as a springboard for discussion but would not necessarily be its continual focus. In effect, what we are envisioning is something that would engage children in the sorts of animated conversations that "cabinets of curiosities" and other private museums spurred among privileged 17th century European intellectuals. (See, for instance, the spectacularly illustrated recent survey *Cabinets of Curiosities* by Mauries (2002)). We might ask, then, which elements of design might provoke (or suppress) conversation, and how those elements can be consciously incorporated into the artifacts that we create. Such considerations are natural to the arrangements of "cabinets of curiosities" and other museum displays, but thus far foreign to the literature of educational computing.

A similar issue involves the ways in which room-sized artifacts might encourage, or discourage, group activities among children. One might imagine a group of children using a large SmartTiles array in ways that would be beyond the powers of a single

child to accomplish; or in teams that might compete to see which of them can keep a simulation “in play” the longest. Educational designers will need to consider those elements of design which permit multiple children to participate in creative ways (or which deliberately limit activity to individuals, if that is more desirable for a given context). For example, an artifact such as SmartTiles has multiple, simultaneously active sites of interaction in that each light acts as its own “localized” interface to the overall display.

Related, Ongoing and Directions for Future Work

As indicated earlier in this paper, our own work has been particularly influenced by the ideas of Mitchel Resnick and his colleagues at the MIT Media Lab (Resnick et al. 1996; 1998); Resnick’s focus on developing artifacts that children can program and control is one that we share. In the same MIT laboratory, the work of Hiroshi Ishii and his collaborators likewise provides many inspiring examples of how computational media can be incorporated into environmental settings (Ishii and Ullmer 1997).⁷ We have also been strongly influenced by the work of Mark Gross and his collaborators at the University of Washington, especially in the area of incorporating computational elements into objects that can be combined in the fashion of construction kits (cf. the work on Navigational Blocks by Camarata et al. (2002)).

We will continue to develop and refine of our SmartTiles prototype, as well as design additional prototypes along similar lines. Our still-in-progress revision of the SmartTiles prototype, for instance, employs smaller, “pocket-sized” tiles. This represents something of an engineering tradeoff, as the smaller tiles require a greater degree of hand-eye coordination to use, but can exhibit a far wider range of cellular automaton behavior and can be more easily carried about from place to place. There are numerous small-scale alterations that could be tried on this particular project in the future (e.g., a more elaborate or powerful programming interface, a larger number of tiles to create a more complex display, and tile elements with a larger number of possible display states). An important future pursuit is the creation of a prototype robust enough to be the subject of long-term user tests in realistic settings; the SmartTiles prototype described in Figure 1, while useful for suggesting what such a real-world device would look like, is not at this level of sturdiness.

More generally, we hope to create several more illustrative prototypes of room-sized interactive artifacts for education. Creating a variety of different artifacts or furnishings, perhaps along the lines of the “fanciful” examples mentioned earlier, would provide us with a body of lore to draw upon in articulating design principles for this still-embryonic, but strikingly provocative and promising, genre of educational computing.

Endnotes

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2. One might plausibly extend this argument by imagining a grain size still larger than the room as a canvas for design—the city block, perhaps, or the neighborhood. Although we feel that design at this larger “community-size” grain would be worthwhile, it should also be noted that community-sized design inevitably involves thorny questions of public policy (e.g., how and where to place educational artifacts within public spaces; how to maintain them in those spaces, and at whose expense; how to ensure their equitable use; and so forth). For the purposes of this paper, then, we prefer to remain at the somewhat less ambitious (and therefore, we believe, more approachable) level of room-sized design.
3. A tasteful counterexample to this caricature of ubiquitous computing can be found in the work of Rogers and Price (2004). Their version of educationally-oriented ubiquitous computing employs child-controllable data collection and visualization devices placed in natural settings (of the sort encountered in field trips and nature hikes). This work exemplifies a philosophy of promoting active, conscious exploration for children rather than one of creating “invisible” labor-saving devices.
4. See, for example, the discussion of the popular “Furby” toy in Pesce (2000).
5. The system to be pilot-tested is in fact a newer version of the one described in this paper; some features of this newer implementation are discussed in the final section.
6. A Quicktime movie showing the SmartTiles in operation can be viewed at the following website:
<http://l3d.cs.colorado.edu/~ctg/projects/smarttiles/SmartTiles.mov>
7. The recent “Topobo” project from Ishii’s lab (Raffle, Parkes and Ishii 2004) also has an educational focus, and an element of end-user controllability. The Topobo construction kit for robotic animals can be “programmed” by moving the pieces of the completed animal sculpture by hand in a way that can be repeated automatically by the sculpture, causing it to move on its own.

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Appendix A: Tile Implementation and Cellular Automata

A SmartTile's overt behavior is represented by a large light, which can be on or off. Thus, each current SmartTile has two display states, and the combination of communicating tiles produces patterns of on-or-off lights. A four-by-four set of SmartTiles was shown in Figure 1; in that figure, seven of the tiles are in their "on" state, and nine are "off." Each of the 16 tiles in Figure 1 can be considered as a single computer, and all of the 16 computers are able to communicate their on-or-off state to their immediate neighbors in the set.

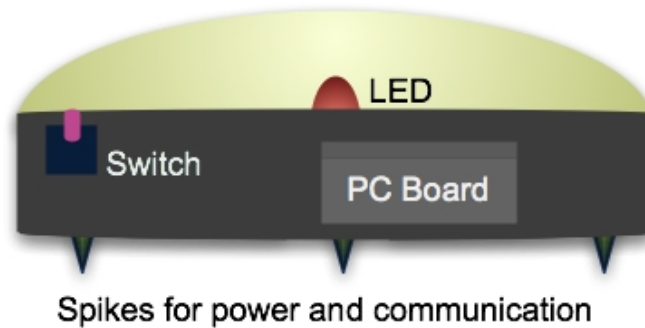
The SmartTiles array illustrates a notion familiar to computer scientists as a *cellular automaton*. Briefly, *cellular automata* (cf. Gardner 1985; Toffoli and Margolus 1987) are regular arrays of simple, locally-communicating computers that operate in synchrony. Each cell in a given automaton can be in one of a small set of "states." (In the case of SmartTiles, then, each tile can be in one of two states, "on" (lit) or "off" (unlit).) At each time-step, all the cells in a particular automaton run their own individual program, whose general form can be summarized as follows:

- a. Note the current state of this cell and all eight local (neighboring) cells surrounding this one.
- b. Based on the pattern of states recorded in step (a), set the state of this cell at the next time-step.

For example, in the most well-known two-dimensional cellular automaton program, J. Conway's "Game of Life" (Gardner 1985), the specific rule is to count the number of lit cells among the eight surrounding cells at step (a) above. If that number is 2 or 3 and the cell's current state is "lit," it remains lit at the next time-step; if the number is 3 and the cell's current state is "unlit," the cell changes to "lit" at the next step; otherwise the cell is "unlit" at the next step. This relatively simple rule, when run by a large array of cells, is capable of giving rise to astonishingly complex dynamical behaviors. Some Game of Life light patterns are "stable" in that they do not change over time; some are "oscillators," moving repeatedly between a finite sequence of states; others give the appearance of moving figures (e.g., the pattern of light called the "glider," which appears to slide diagonally across the array). In short, the Game of Life is a marvelous laboratory, in and of itself, for exploring a huge range of important ideas in experimental mathematics. Of course, the Game of Life represents just one particular choice of cellular-automaton program. Other cellular automaton rules (of comparable simplicity) have been used in numerous simulations of complex physical and chemical systems (see Toffoli and Margolus (1987) for a variety of remarkable examples).

Each individual SmartTile is constructed from a large light controlled by an embedded computer. The light can also be switched on and off (if desired) directly by the user; this is accomplished by pushing on the light's surface. SmartTiles do not have their own individual power source; rather, they are placed into a background fabric that provides both for communication between neighboring tiles and for power. A schematic of an individual SmartTile is shown in Figure 2.

Figure 2. A schematic diagram of a single SmartTile. The LED is the tile's light; the PC board is the embedded computer.

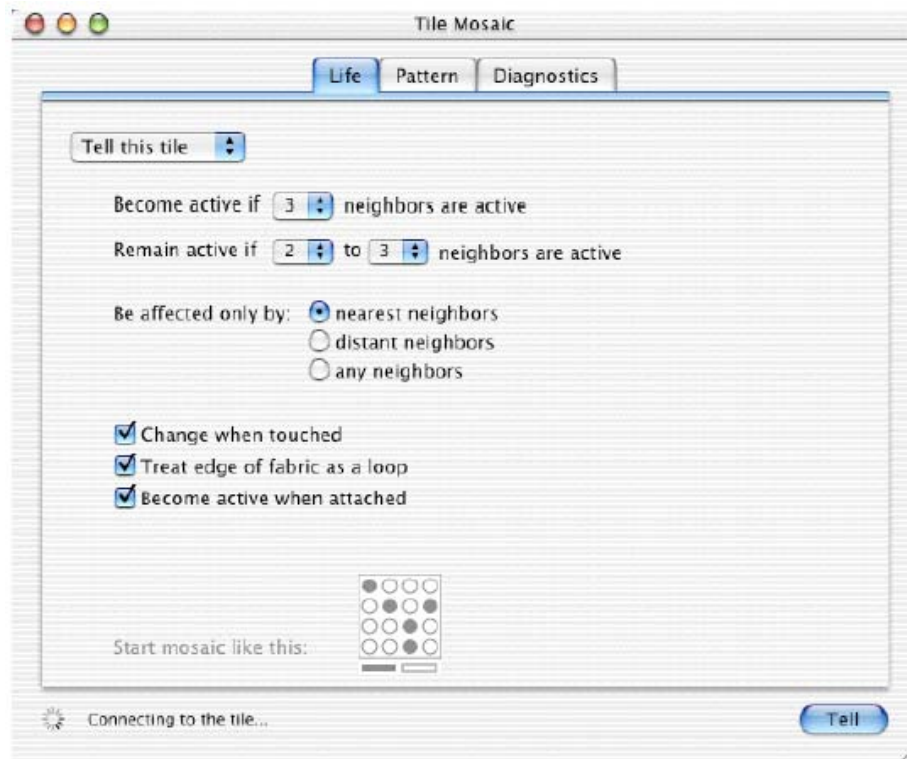


In a typical scenario, a set of SmartTiles is each given a particular program to run (such as that summarized above for the Game of Life). The entire set of tiles is then instructed to run their programs, obtaining power and finding neighboring tiles via the background fabric in which they are placed. Any large surface that can accommodate the background fabric can accommodate a set of SmartTiles.

Again, the state of a tile is controlled not only by its associated program, but also by direct interaction with the user (or users). Thus, a group of children in the presence of a set of SmartTiles could affect (or even, in some circumstances, control) the behavior of a given automaton by pressing lights at strategic moments, directly setting the states of individual cells in the course of a running simulation and changing the subsequent patterns of activity in the set.

In most cellular automaton examples, all cells are running an identical program at each time step. SmartTiles, however, may be removed from the background fabric and individually reprogrammed. Thus, for example, one could create a SmartTile array in which most cells happen to run the Game of Life program at each time step, while several selected cells run a distinct program (e.g., they might remain "on" indefinitely, independent of the behavior or states of their neighbors). SmartTiles can be reprogrammed with a desktop machine that has a reprogramming software system. We have implemented such a system, and the programming interface is shown in Figure 3. This programming system is still rather limited, and based on a constrained set of menu choices, but it suggests the range of customization that could be implemented in a fuller system. In the Figure 3 example, the user has selected values for individual menu choices that correspond to the Game of Life parameters. (One of the "special" choices shown toward the bottom of Figure 3—the one dictating that the edge of the background fabric can be treated as a "wrap-around" edge that communicates with tiles at the opposite edge as neighbors—is not operational.)

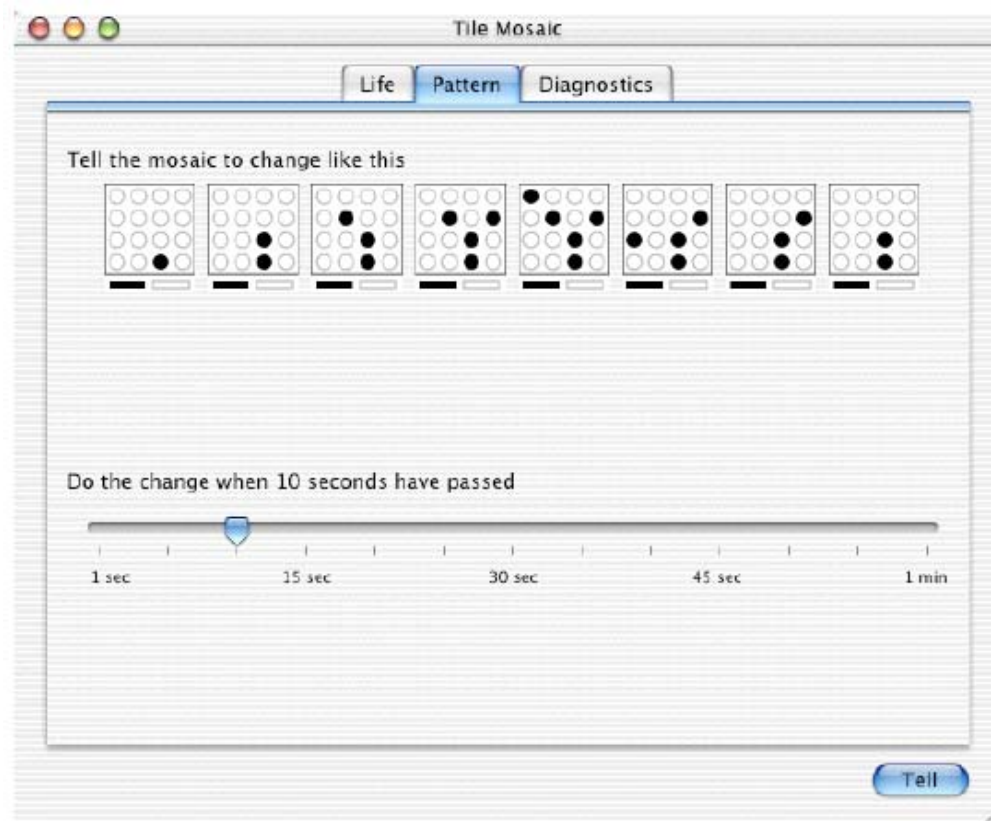
Figure 3. A view of the current SmartTiles (re-)programming interface



It is also possible to program entire, global sequences of behavior for the SmartTiles array—essentially programming the entire background fabric. A separate portion of our programming interface, shown in Figure 4, permits the user to program relatively brief cycles of tile patterns, and allows the user to specify a particular pace at which these cycles will be displayed. The sequence in Figure 4, for instance, would cycle through a sequence of states consisting of one lit tile (the configuration at the left), followed by the two vertically-arranged lit tiles (the second configuration), and so forth.

The programming system that we have implemented is in fact much simpler (and less powerful) than a full-fledged SmartTiles programming system might be. (For example, one might imagine a tile program that alternates, at each time step, between following a Game-of-Life algorithm and a “don’t-change-regardless-of-neighboring-states” algorithm.) The computers embedded within each SmartTile, although small, have enough memory to implement significantly more elaborate programs than those allowable through the interface seen in Figure 3. The intent of our current programming system is thus not to represent the full capabilities of a room-sized cellular automaton artifact, but rather to suggest what a more powerful system would look like. Our current system could be thought of as a “novice-level” system that children could use to create simple cellular-automaton programs, while more advanced users could employ a more complex programming interface.

Figure 4. Dictating sequences of display patterns with another portion of the programming interface



Appendix B: Room-Sized Educational Artifacts—Technological Challenges and Opportunities

Technological Challenges

Although any project such as SmartTiles will present its own unique technological challenges to implementation, the general practice of creating room-sized educational artifacts does, we believe, pose recurring problems for designers. In exploring these problems here, we hope to provide prospective designers with at least some guidelines toward solutions.

Programmability, Reprogrammability, and Power

We believe that an essential element of the design of room-sized artifacts is their controllability by their young users. In most cases—since these artifacts will most likely derive their behavior from embedded computation—"controllability" is a rough synonym for "programmability." The programming that a child might undertake cannot be highly sophisticated; in our own interface, this "programming" is done via a number of menu choices that customize behavior. The resulting behavior of the

SmartTiles array can be more complex than this set of simple choices implies, however, since each individual tile may run its own unique program.

However, the proper design of end-user programming systems has long been a controversial subject.¹ One of the major sources of contention is the issue of users' ability to learn the skills of programming. There is a widespread (although not universal; see diSessa 2000) perception that programming is a prohibitively difficult skill to learn. This thinking is the motivation behind research efforts in programming-by-example and other techniques developed to lower the barrier to program creation (Cypher 1993). Our belief is that many of the traditionally thorny issues in children's programming (e.g., their ability to create complex programs, to understand large bodies of program text, etc.) lose some of their sting in the context of room-sized artifacts. A cellular-automaton "cell" in an artifact such as a SmartTile rarely needs a program of more than about a dozen lines to provide the overall automaton with a great deal of sophistication and complexity.

More generally, since the artifacts that we imagine are envisioned as programmable physical objects, the types of programs written for them are likely to be tightly linked to a relatively constrained repertoire of physical actions. Consider what it might mean to write a program that "runs" within one of the "interactive furnishing" examples mentioned earlier, such as a mobile, or window-curtain, or carpet. Even very simple programs in these physical artifacts can give rise to profoundly interesting and complex behaviors because users can affect the programmed objects directly. For example, with an artifact like a SmartTiles array, multiple users might interact with a running program in midstream, or the simple programs within each tile can interact with one another. Further, the complex input of the surrounding environment might make a simple program behave in unpredictable ways: consider, e.g., how a "programmed window-curtain" might react to different patterns of sun, shade, or wind, even if the artifact itself possessed only a simple program. In short, then, we believe that room-sized artifacts can be programmed with simple, short and understandable programs without sacrificing the potentiality of complex or interesting behaviors. In this respect, the traditional controversies over end-user programming are less daunting in the context of programming physical objects.

However, room-sized artifacts introduce new end-user programming issues. Consider, for instance, reprogramming a particular array of SmartTiles: if a child wishes to alter the program of, say, ten individual tiles, the child must remove each one of the ten in sequence and bring them to a desktop machine for customization. This sort of issue rarely arises in traditional programming systems, for the simple reason that the programmed artifact (the desktop machine) is typically in the very same spot as the software system used to program it. For the sorts of artifacts that we imagine, however, programming and use may take place in widely different geographic settings.

A natural design principle, then, for room-sized artifacts might be to permit them to be programmed (and reprogrammed) via handheld or portable devices. The next step will be the ability to program sets of objects such as tiles or portions of a

larger object (e.g., struts in a mobile, or patches of carpet) *en masse*, so that one does not have to do the same programming chore many times in repetition. Another use of a handheld programming device might be to “read in” or reveal the programs currently running in a given array.

Another programming issue with potentially large, room-sized artifacts is the challenge of being able to “read in” a program from a portion of the artifact that one cannot reach. Similarly, how might a child be able to retrieve a tile for reprogramming that happens to be up toward the top of a tall wall? The designer of room-sized artifacts must thus confront novel interface issues that have little historical precedent in classic, screen-based programming environments.

Yet another important technological design issue for room-sized artifacts is the arrangement and provision of power sources. In our initial discussions of the SmartTiles project, we imagined that each tile would have its own individual battery or power source; indeed, if the tiles were to be placed in an outdoor setting and could run off say solar cells, that might well be an advantageous way to design them. However, for tiles placed in interior settings, individual batteries introduced the prospect of individual cells “going dead” at unpredictable intervals. Therefore, we elected to provide the tiles with a power source from a background material into which they are placed. This solution is, as most design solutions are, a compromise between constraints: it permits us to create tiles without batteries, but at the same time it necessitates a particular substrate into which tiles must be set. It might be delightful to have tiles that could be affixed to arbitrary surfaces such as brick or plaster walls, but in that case, the power source for each tile would have to be provided individually or via some means other than through the backing material itself.²

Technological Opportunities

The previous discussion focused on several technological problems that are likely to recur in the design of room-sized educational artifacts. But it should also be mentioned that there are a variety of recent technological developments that present tremendous opportunities—new affordances—for the creation of these sorts of artifacts. Certainly, the widespread availability of commercial devices for experimenting with embedded computation (such as the PIC microcontroller or Basic Stamp) makes it increasingly easy to create, or at least prototype, novel designs. There are other, equally exciting developments in the design of “smart” materials that can change shape, size, color, transparency, or viscosity in response to computationally-controlled signals (Eisenberg 2003). By employing these materials in room-sized artifacts, we can endow children’s environments with a formidable range of behaviors: windows might change their opacity in response to certain inputs; wall hangings might change color in response to sunlight or touch; mobiles might change their physical dimensions over the course of a day.

Still another exciting development can be found in the increasing availability of fabrication devices such as laser cutters, milling machines, and 3D printers (Eisenberg 2002). By combining these devices with the design of room-sized artifacts, we can imagine interactive objects that children can not only control but

can (at least in part) build. Customized casings for SmartTile-like objects might eventually be fabricated to create surface overings with unexpected appearances. For example, a large, interactive Rube Goldberg-style machine might be placed in a classroom or school lobby; customized, machine-specific pieces of that large device could be “printed out” from a 3D printer and added to the working display. Again, such examples are a bit futuristic, but they reflect a convergence of related technologies for integrating physical and computational media.

Endnotes

1. See Nardi (1993) for an excellent overview of the issues surrounding programming by end-users of computer applications.
2. Going a bit further, we feel that the creation of room-sized artifacts should and will give rise to a variety of interesting experiments with power sources (cf. the brief discussion in Gershenfeld 1999, pp. 50-52). Many of these artifacts could conceivably be “powered” simply by human activity or participation (e.g., a programmable room-sized artifact might lie “dormant” until moved, pumped, or heated by its user); others might be placed in settings where power can be provided by normal outlets.