Invisibility Considered Harmful: Revisiting Traditional Principles of Ubiquitous Computing in the Context of Education

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Abstract

Ubiquitous computing, as a subfield of computer science, has traditionally been associated with a set of principles expressed (loosely but tellingly) with terms like transparency, invisibility, *and the like: essentially, the idea is that people should be able to use ubiquitous computing artifacts while hardly being conscious that they are doing so. We argue that, as a design principle, "invisibility" has advantages in some domains; but that it has powerful, and ultimately counterproductive, connotations for educational design. We present an alternative set of potential design principles for educational ubiquitous computing, stressing values such as expressiveness, creative control, and aesthetics; and we illustrate these principles with several projects undertaken in our lab.*

Keywords
Ubiquitous computing and education; transparency; educational technology.

1. Introduction: the Problem of "Transparency"

Like many names that denote research areas, *ubiquitous computing* is a term that allows for some creative diversity in its definition. Researchers pursuing the design of "ubiquitous computing" artifacts sometimes focus on embedding computation into objects in the physical environment; or they might focus on techniques by which a group of such tangible computational entities may communicate with one another; or they might focus on means by which these entities can interpret human behavior, or adapt to specific contexts of use.

Despite the wide variety of approaches covered by the term "ubiquitous computing", the field nonetheless has something of a tradition–an underlying philosophy of design that can be traced back for at least a decade and a half. This philosophy is not, of course, a stringent rubric for design; nor do computer scientists necessarily make explicit reference to it in their research papers. Nonetheless, the tradition plays a subtle but powerful role in that it influences basic ideas about what ubiquitous computing is *for*, what its ultimate purpose is; and these ideas in turn impact decisions about what is worth designing and how to assess those things that are designed.

The most eloquent and compelling early expression of this philosophy can be found in the writing of the late Mark Weiser. Weiser's influential 1991 *Scientific American* article on ubiquitous computing [12] began with the words:

> The most profound technologies are those that disappear. They weave themselves into the fabric of everyday life until they are indistinguishable from it.

Shortly thereafter, the article continues:

> [W]e are trying to conceive a new way of thinking about computers in the world, one that takes into account the natural human environment and allows the computers themselves to vanish into the background.

In yet another paper, this one in *Communications of the ACM*, Weiser [11] writes

> The point is to achieve the most effective kind of technology, that which is essentially invisible to the user.... I call this future world "Ubiquitous Computing".

Echoes of these themes can be found in numerous subsequent papers and presentations in the field of

ubiquitous computing, associated with terms such as "transparency" and "invisibility" (the latter is the more common term in Weiser's writing, but both are employed in similar contexts by other writers). Essentially, the point of view suggested by these terms can be summarized (at the risk of a bit of caricature) as follows:

• Ubiquitous computing focuses (or should focus) on technology that "gets out of the user's way". Conceivably, the "user" (in some standard scenario) may not even be aware of the presence of the computer at the point of interaction.

• The user's goals or activities should not be primarily defined in terms of the computer (e.g., "saving a file" or "running a program"); rather, these activities are defined independently of the computer (e.g., "locating a colleague in one's office building", "remembering a person who was at a meeting"), and the computer's job is to facilitate (again, "invisibly") this goal.

Weiser's beautiful writing is persuasive and passionate, and for many purposes his portrait of ubiquitous computing is appropriate. For education, however, we argue that a focus on "invisibility" in ubiquitous computing is problematic–and even counterproductive. A portrait of *ubiquitous educational computing* is needed, then, as an alternative to the traditional vision of the field. The purpose of this paper is to suggest at least the outlines of such an alternative portrait, keeping in mind not only the technological affordances of ubiquitous computing but also the particular purposes and challenges of education. In presenting this portrait, we employ projects underway in our laboratory as a source of examples and springboard for discussion.

The second section of this paper begins this argument with a set of alternative themes for design in ubiquitous educational computing:

(a) *Curiosity enhancement* as a means of diffusing the presentation of content and ideas throughout situations in the everyday world;

(b) *Control and programmability* as a means of enhancing students' expressiveness and creative participation in educational activities; and

(c) *Aesthetics* as a means through which ubiquitous computing can cultivate motivation and intellectual growth.

The third section of this paper concludes with a suggested research agenda appropriate to this alternative philosophy of ubiquitous computing, and contrasts it to a (less productive, in our view) agenda suited to the traditional philosophy.

2. Three Central Themes for Ubiquitous Educational Computing

In this section, we present what we consider to be three foundational themes that should inform the design of educational artifacts in ubiquitous computing. As a preface to these themes, it is perhaps worthwhile to reflect briefly on why education presents special challenges and opportunities for design in this area. Or, to put it another way: why should there be a different set of values for ubiquitous *educational* computing, in contrast to values for other sorts of ubiquitous computing?

Our own feeling is that educational design, at its best, is geared toward several crucial aspects of children's lives: fostering interest and motivation, encouraging participation in intellectually rich activities, communicating important or central ideas in different areas of subject matter, and cultivating creativity and personal expressiveness. Thus, the creation of ubiquitous computing artifacts should be in the service of these educational goals. The special affordances of ubiquitous computing in this regard stem from being able to design new types of children's activities (e.g., with responsive tangible artifacts, or in outdoor settings) and new types of physical settings in which children can work and play (e.g., computationally-enhanced playgrounds, classrooms, science museums, and so forth). Ubiquitous computing offers educational designers remarkable new territory to explore in the pursuit of enriching children's lives.

The values of "invisibility" and "disappearing technology" tend, if anything, to run counter to educational goals. When technology is invisible, it is deliberately placed outside the user's awareness; thus, there is little reason to communicate how the technology in fact works, and how the user might extend or control it. When one is unaware of technology–when the technology has "disappeared into the background"–it is unlikely that one will

become curious about its design. In effect, then, the values of "invisible technology" are geared more toward scenarios of office work, or professional business. In these settings, the user is not especially encouraged to let their mind wander off in bouts of curiosity–that would only detract from the job. Moreover, a professional office worker has particular tasks to do–tasks that technology can make more efficient or reliable (e.g., remembering the name of a professional contact). For such tasks, however, creative personalized expression is rarely a high priority: the point is rather to achieve some business-related task with a minimum of error and distraction. Invisibility is an appropriate desideratum for technology in such a setting–but not in education.

2.1 Curiosity Enhancement: Ubiquitous Computing as a Means of Conveying Ideas

One of the affordances provided by ubiquitous computing in education is the possibility of diffusing opportunities to convey interesting ideas or subject matter to students in meaningful settings. All sorts of physical artifacts might be seen as opportunities to convey subject matter content: a mobile might change its own configuration to illustrate ideas of balance or center of gravity; a fountain might display (or permit control of) complex phenomena in fluid flow; a terrarium might permit measurement of animal activity; a playground swing might be designed to convey ideas about the physics of resonance.

In sixteenth and seventeenth-century Europe, "cabinets of curiosities" were a popular means among aristocrats of stimulating intellectual conversation and interest. Essentially, these were "home museum displays"–often they included (e.g.) seashells, preserved plant and animal specimens, minerals, and other types of objects that would later be gathered into more formal presentations in public museums. [7] Our argument is that ubiquitous computing offers designers a fascinating opportunity to reinvent the idea of the "cabinet of curiosities" for young children. Children (and adults) can now design, control, and customize objects whose status is somewhere between that of a scientific display and a work of art–objects whose express purpose is to convey interesting ideas and spark conversation.

One example, from our own work, of how ubiquitous computing artifacts can convey subject matter is through the use of computational "tiles" that cover surfaces. We have designed a set of SmartTiles that

are small programmable tile-like pieces that can be combined into arrays. Each SmartTile contains a microcontroller, LED, and piezoelectric touch sensor; and the tiles may be placed in a background fabric that supplies communication connections (between neighboring tiles) and a source of power. Essentially, then, each tile is an independently programmable element that can be placed into a larger set of tiles to produce complex cellular-automaton-like displays. (Our more recent version of the SmartTile is also equipped with an infrared sensor so that it may be programmed directly and wirelessly via a handheld computer.) Figure 1 shows a ten-by-ten array of SmartTiles–in this case, each of the tiles has been programmed with the same rule corresponding to the well-known "Game of Life" cellular automaton. [5]
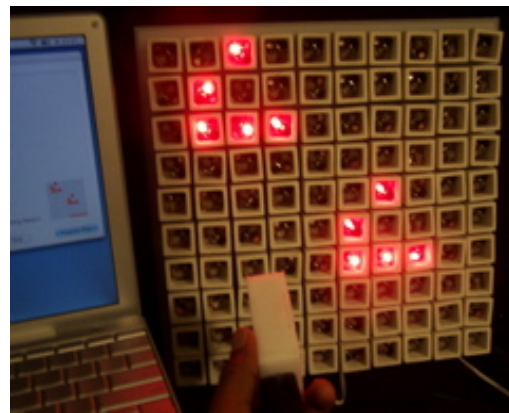
Figure 1. A ten-by-ten SmartTiles array running the "Game of Life" cellular automaton simulation.

Space does not permit a thorough description of the SmartTiles system here; and the project has been described at greater length in earlier publications. [3,4] For the purposes of this discussion, the essential point is that SmartTiles may be seen as a means of producing ambient, highly controllable displays that illustrate important ideas in the field of dynamical systems–stable states, oscillations, chaotic systems, reversible and irreversible systems, and so forth. In effect, the tiles become a means by which a child's room (or a classroom, or a public space) can take on the aspect of a cabinet of curiosities–surfaces of various sorts (walls, doors, countertops) can be stimulants to conversation and investigation.

SmartTiles represent one approach to "curiosity enhancement" for educational ubiquitous computing, but this is by no means the only such approach. The

larger point of this example is to suggest ways in which the artifacts and materials that populate children's environments can be enriched, by computational means, to convey or display important or complex subject matter.

Note, again, that this style of design runs counter to the ideal of "invisibility" or "disappearing technology". In SmartTiles–and in many other conceivable examples–not only is the technology visible, it is conspicuous: the design is based on making the technological artifact compelling and provocative, rather than placing it outside the user's conscious awareness. Moreover, the point of SmartTiles is affirmatively not to make some other task more efficient, reliable, or labor-saving; the tiles are intended to (occasionally) grab one's attention and induce intellectual amusement. They occupy a surface merely for their own sake, much like a cabinet of curiosities display.

Finally, it is worth noting that the tiles are programmable and controllable by their users: each tile may be endowed with its own independently-running cellular automaton-like rule. (For instance, one tile might run the "Game of Life" rule while its neighbors obey some alternative rule dictating the tile's appearance over time.) This observation leads us in turn to the second of our design themes.

2.2 Control and Programmability: Turning Ubiquitous Computing Artifacts into Means of Expression

One of the most provocative aspects of ubiquitous educational computing lies in the possibility that students may be able to produce controllable (and often complex) behaviors in physical objects. Rather than being limited to "screen-based programming languages", whose effects are confined to the desktop, students can create programs that make things-in-the-world take action. A marionette might combine handheld operation with programmed behaviors; a bicycle might be equipped with a programmable display whose operation is influenced by the actions of the rider; a set of wind chimes could be augmented with programs that cause the chimes to produce distinct sounds in response to distinct patterns of wind. Or, to take an example or two from the previous subsection, one could imagine making such things as mobiles and fountains programmable as well.

This approach has been pioneered in education by the work of Mitchel Resnick and his colleagues at the MIT Media Lab; much of their research has focused on the use of the "programmable Lego brick" to create an astonishing variety of programmable constructions. [9] Resnick's work illustrates the rich potential of giving students the means to program physical objects; but there are innumerable other avenues to explore within the general area of "tangible programming for children". (See also, for example, [8] and [14].)

In our lab, ubiquitous computing artifacts–like the SmartTiles–are typically designed to be programmable by their users. Another example along these lines is in the design of "programmable wearables". Here, the idea is that children can have the tools and techniques with which to create programmed display effects on articles of clothing. Figures 2 and 3 present two working examples of this idea: a programmable bracelet and tanktop shirt. In both cases, the display elements are arrays of "LED sequins"–lights that can be attached to fabric and sewn into arrays via conductive thread. Both the bracelet and shirt are also equipped with a tiny battery and microcontroller; overall, then, these articles of clothing can be programmed to produce a huge variety of visual effects. (We have produced both cellular automaton programs and scrolling text, among other displays, on these items.)
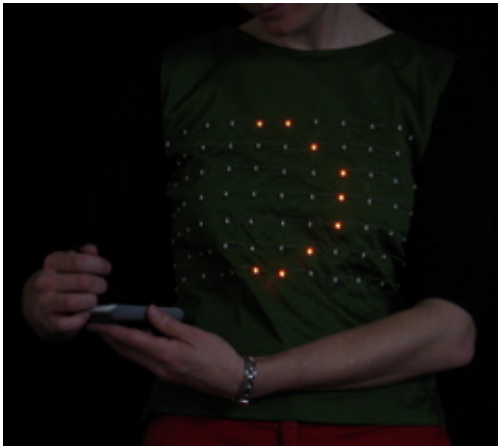
We are currently developing a programming interface that permits students to send their own (in some cases relatively simple) custom-written programs to articles like the bracelet and shirt. Figure 3, in fact, shows the wearer "reprogramming" her own shirt using a handheld PDA device. In this particular case, the "reprogramming" simply changes the initial pattern of lights on the garment; the new initial pattern then evolves in accordance with the already-existing cellular automaton rules. Figure 4 continues our example with a view of the PDA screen being employed for this type of reprograming: here, a new starting pattern is created which can then be sent via an infrared signal to the tanktop microcontroller. A much more powerful and general type of handheld "reprogramming", which we are developing for the SmartTiles and potentially a variety of wearable articles as well, would involve sending new underlying cellular automaton rules (rather than just starting patterns) to an object via the PDA.

Figure 2. A programmable bracelet with an array of LED sequins as a display.

Figure 3. A programmable tanktop shirt. Here, the wearer is "reprogramming" the shirt wirelessly with a new starting cellular automaton pattern.

As before, there is insufficient space to give a detailed description of our programmable wearables. The fundamental point is that these are ubiquitous computational artifacts that can be controlled by their users. In more general terms, we argue that ubiquitous computing can provide new sorts of creative avenues of expression for students–physical objects can become new types of artistic media, in the spirit of musical instruments. (Cf. [10] for a wonderful discussion of just this sort of analogy.)

Figure 4. A close-up of the handheld PDA interface for reprogramming the tanktop shirt in Figure 3.

Programmability is a design theme that again runs counter to the tradition of "invisibility". Indeed, one might argue that to the designer who pursues invisibility, giving the user this sort of deep control over a computational artifact is the *last* thing one wants to do; programmability is seen as a burden rather than an opportunity. We believe, in contrast, that education is an enterprise that should encourage students toward personal expression and expertise. It may indeed take some work to program displays into one's clothing–just as it takes work to learn to play a musical instrument; but in both cases the result can be unique, personal, and creative.

2.3 Aesthetics: Making Beautiful Ubiquitous Computational Artifacts

Weaving computational media into physical objects affords both designers and students the potential for treating educational settings as objects of design. That is, rather than thinking of *programs*, or even computationally-enhanced artifacts, as the objects of educational design, we can think of the *room or setting itself* as the object of design. Ubiquitous computing allows us to enhance, profoundly, the aesthetic dimension of educational settings and materials. This in turn suggests that the places in which children work, play, and learn can be more motivating, playful, comforting, or stimulating (depending on the style of environmental design).

The design of children's environments has long been a subject of study and discussion in educational circles–early theorists such as Maria Montessori and Friedrich Froebl had strong notions of how to design
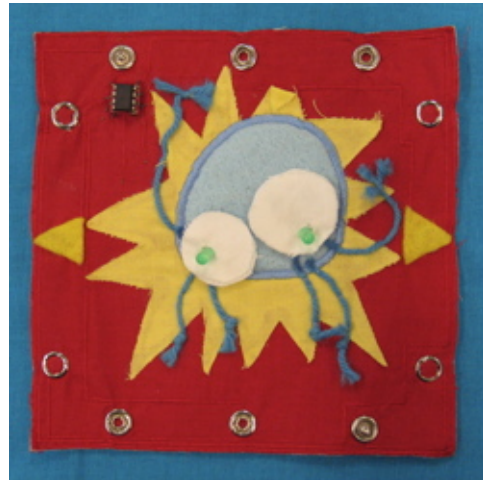
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school settings [cf. 6]. Still, there has been little effort to rethink these theories of childhood development in the light of advances in ubiquitous computing. Computational artifacts might be employed as decorative devices, gorgeous dynamic mathematical displays, or programmable artwork. One might employ computational techniques to produce dynamic effects in dioramas or murals; physical objects with complex behaviors might be blended into model railroad scenery, dollhouses, or racetracks; even standard classroom decorations (such as the periodic table, or geographic maps) could conceivably be enhanced with computational effects.

One example from our lab–a project named *Quilt Snaps*–illustrates how the aesthetic dimension may be blended into ubiquitous educational computing. Quilt Snaps are computationally-enhanced square patches of fabric which can be composed together to form "dynamic quilts". Each Quilt Snap piece includes an embedded processor and metal snaps corresponding to "input" and "output" directions; each piece also can be decorated with both electronic elements (such as LED lights) as well as "low-tech" elements such as patches of felt and hand-drawn marker patterns. Figure 5 shows a sample Quilt Snap piece; the top and bottom edges of the piece have "input" snaps, while the arrows at the left and right edges indicate that these are "output" edges. When an input signal is received by the quilt, the LED eyes of the spider light up; and after one time unit, output signals are sent to neighboring patches (if any) to the left and right. [1]

Figure 6 shows a set of Quilt Snap patches linked together; each patch is individually decorated, and depending on the ways in which patches are combined, signals might traverse the overall "quilt construction" in numerous ways, Special "touch sensor" and "light sensor" patches enable the user to start a signal moving along the quilt.

Quilt Snaps represent an attempt to take decorative children's crafts, augment those crafts with computation, and employ them in the fashion of a construction kit. Each patch can be a personal creation by a student, employing any number of decorative techniques; combined, the pieces constitute a dynamic, reconfigurable program that can act as a wall hanging (if many patches are employed) or as a decoration for a jacket or backpack (if at most a few patches are employed). Moreover, the decorative or aesthetic elements are integrated with the computational behavior of the patches: a

given patch might have a creature with a "light-up nose", a mathematical pattern in which lights highlight a particular set of points, or a twinkling constellation of stars. (Patches can also be equipped with sound generators so that they respond with tones instead of lights to an input signal.)

Figure 5. A decorated Quilt Snap patch.

Figure 6. A collection of Quilt Snap patches connected into a "quilt program". The Figure 5 patch is visible at bottom right.

Focusing on the aesthetic dimension of ubiquitous computing artifacts should be a recurring consideration in educational design. But again, this is a dimension that tends to be suppressed by an emphasis on "invisibility". After all, "invisible" technology is not supposed to call attention to itself;

while decorative artifacts are not merely visible, but exuberantly attention-getting.

3. Ubiquitous Educational Computing: Implications for Research

The previous section presented three themes that (in our view) should characterize the emerging field of ubiquitous educational computing, in contrast to the traditional (non-educational) vision of the field. In this section, we draw out several implications of this alternative portrait of ubiquitous computing, and suggest areas of research consistent with the themes of the previous discussion.

The first theme–using ubiquitous educational computing to convey important subject matter–initially suggests that we might explore aspects of subject matter that are usually deemed difficult to convey on a computer screen. Indeed, some of the most compelling examples in ubiquitous educational computing are employed to study topics such as disease transmission [2] and natural phenomena (such as plant growth) in outdoor settings [13]. There are still other ways in which ubiquitous educational artifacts can introduce otherwise problematic material. For example, an ambient display that runs in a child's room over a period of weeks or months could be used to convey the unfolding of processes that take a long period of time: a representation of the moon, for instance, might circle the walls of the room over the course of a month, or a physical representation of a butterfly's life cycle might play out over the course of a summer. Large physical, as well as temporal, scales can also be exploited: a SmartTiles-like display over the side of a building could convey the behavior of a large complex system in ways that would be far more viscerally effective than anything possible on a desktop screen. Again, the central element in considering these possibilities is not to seek invisibility, but rather to understand what makes computational artifacts capable of sparking curiosity and conversation.

The second theme–endowing ubiquitous educational artifacts with programmability–raises a host of research issues that have the potential to reinvigorate the subject of children's programming. Rather than limiting children to producing screen-based effects in their programs, ubiquitous programming tools offer children the possibility of controlling a wide variety of physical behaviors (often through the use of very brief programs). Moreover the possibility of writing programs to control the behavior of (e.g.) one's own articles of clothing, or the decorations in one's own room, could be particularly motivating to children in ways that traditional programming often is not. A teenager creating a program for his or her wardrobe might represent a pioneer in a new type of programming culture (in contrast to the traditional "hacker" stereotype primarily interested in, say, game design or other screen-based activities).

Even programming languages for children might look somewhat different when those languages are tailored for ubiquitous computing artifacts. For example, one might create a "program browser" in which a student first selects a sample program based on the physical behavior that it produces; to pursue the example of wearables, our hypothetical student might look through a video library until he finds an example of a "light-up hat" that piques his imagination. Once he finds a description of the program that generated this effect, he can then alter the text of the program to produce his own particular variation. The point of this example is merely to suggest that apparently familiar notions such as "program reuse" or "software libraries" can look very different in the context of ubiquitous educational computing.

As for aesthetics, the affordances of ubiquitous educational computing allow researchers and designers to explore new types of questions. For instance, a desktop screen tends to command one's attention for a relatively limited time, and in relatively deliberate ways: when the software application is quit, or when the computer is turned off, one's attention turns elsewhere. In contrast, a program that runs "in the background" in an extended setting, over the course of an extended time, is likely to elicit a different kind of response. To take a specific scenario, we can once more imagine a child's room in which a representation of the moon (whether graphical or tangible) circles the setting over the course of a month. How does a child respond to this sort of programmed effect in contrast to the sort of effect localized on a desktop screen? Does her attention turn to the "moon" at particular intervals, or on particular occasions? Does she point out the simulation to visiting friends? Does she interact with the simulation in other ways (e.g., sitting or sleeping in different positions over the course of a month as the "moon" travels about her room)? The aesthetics of ubiquitous educational computing artifacts seem not quite identical to those of (non-programmed) artwork or displays; nor do they seem identical to those of screen-based computing, or children's museums, or classroom decorations. Indeed, the

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aesthetics of ubiquitous educational computing appear to be curiously novel and provocative, suggesting patterns of appreciation and interaction that can play out over long periods of time and in unexpected physical and social settings.

In none of these matters–presentation of interesting content, programmability, aesthetics–are the values of "invisibility" or "disappearing technology" paramount. A research agenda focused on invisibility tends to judge success by measures such as productivity, ease of use, and speed of task completion–all metrics suited to the needs and demands of professional office work. When we wish to schedule a meeting, we don't want a creative or expressive tool to do so, nor do we particularly expect our curiosity to be awakened; we just want to schedule the meeting, and the more invisible the technology, the better. The values of education, though, are different: here, our goal is not to save time, but to help children find an intellectual purpose in life. The technologies that assist in this process need to promote curiosity, permit expressive control, and look beautiful. And to accomplish these things, they need to be openly, proudly, and extremely visible.

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