Pervasive Fabrication: Making Construction Ubiquitous in Education

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Abstract— **The notion of "pervasive computing" has traditionally been identified with a focus on what might be called "pervasive processing". This paper, in contrast, argues that the notion of pervasive computing can be profitably extended to accommodate the burgeoning potential of educational fabrication. We present several projects under way in our lab–projects that illustrate how fabrication devices can be employed in educational settings. We then use these examples to motivate a broader discussion of scenarios for "pervasive fabrication" in education.**

Index Terms— **Pervasive fabrication, educational technology.**

I. INTRODUCTION: THE ROLE OF FABRICATION IN EDUCATION

Just as "computing" is often implicitly identified with the central processing unit (CPU) of traditional computer architectures, the notion of "pervasive computing" is often implicitly identified with what might better be called "the pervasive CPU". That is, when computing is made pervasive, the reigning assumption is that this will take the exclusive form of very small *processors*–such as handheld computers. But in fact, much of the burgeoning power of today's computational environments stems from what are (misleadingly) termed *peripherals*–those artifacts, like printers and fabrication devices, that link the computer to the world of physical input and output.

Despite their power, output devices–and computer-controlled fabrication more generally–are still under-explored dimensions of educational technology [5], though to be fair there are exceptions to this observation [e.g., 7, 12]. In the realm of pervasive computing, it is arguably the case that "pervasive educational fabrication" is a subject in its very earliest infancy. This paper is an attempt to argue for a broader view of pervasive computing–one that encompasses and makes creative use of those same fabrication technologies that hold such promise in the world of desktop computing.

Before embarking on an argument for pervasive fabrication, though, it would be best to begin by making the case for fabrication technologies in education more broadly. Why should educational technologists be interested in these devices? Briefly, the answer is that these new technologies can vastly extend and reinvigorate the best traditions of student-driven design and construction. Historically, children have often found powerful educational content and motivation in the process of building and fashioning things–out of paper, string, felt, and many other materials. In the current environment of "virtual worlds", such homespun activities may appear outdated, but they continue to offer children an irreplaceable venue for working with, and understanding the properties of, physical "stuff". (See [6, 10] for more thorough discussions along these lines.) New fabrication tools and devices do not, in our opinion, threaten to uproot this tradition but rather have the potential to enrich it tremendously. The use of (e.g.) laser cutters to work in wood or plastic, 3D printers to create objects in plastic, plaster, or metal, and computer-controlled sewing machines to work in fabric–among many others–can enable us to re-imagine the desktop computer as the heart of a new type of "shop". This in turn means that many educational artifacts that children enjoy, but traditionally have not been able to build–tops, geometric puzzles, customized construction kit pieces, scientific apparatus, to name a few–are now within the range of children's design.

The following section presents a number of projects from our laboratory–projects that serve to elaborate the brief argument of the previous paragraph, and (we hope) communicate our excitement and enthusiasm for educational uses of fabrication. In the third section of this paper, we use these examples as a foundation for discussing the notion of pervasive fabrication: that is, we try to imagine ways in which the power and advantages of educational fabrication can be broadened and augmented by making it much more compatible with the values (portability, ubiquity, accessibility, interoperability) of pervasive computing.

II. FABRICATION IN EDUCATION: ILLUSTRATIVE EXAMPLES

In our laboratory, we have undertaken a number of projects whose purpose is to explore and demonstrate the power of fabrication devices in mathematics and science education. Several recurring themes have emerged in the course of this work–the role of construction in decorating or ornamenting educational settings, construction as a means of personal expression, and the use of construction as a conceptual lens through which to look at the physical and natural world. Here, we (very briefly) illustrate these themes through several representative projects; in the third section we will connect these themes to the emerging world of pervasive computing.

A. Construction and Ornamentation

One of the most surprising affordances of the new range of fabrication devices is that they allow students to decorate–even beautify–their own physical settings (both in school and at home). Fabricated objects take on the role of home or classroom displays; and through these displays, the child's environment begins to take on some of the best features of a creative studio or science museum. In effect, by making high-quality objects, students can be given greater control over the visual and intellectual content of their own physical surroundings.

Do such decorative activities have educational value? There is at least anecdotal evidence to suggest that the answer is yes. When professional scientists reflect back upon their own childhood interests, it is not uncommon for them to volunteer reminiscences about the ways in which they arranged their settings to reflect their emerging interests and professional identities. Just to focus on a single representative source: several of the autobiographical essays in the recent compilation *Curious Minds* [3] highlight this theme. The physicist Lee Smolin, for instance, recalls that "[In high school] my room filled up with models of geodesic domes and other exotic structures" [p. 75]; the cognitive scientist Robert Sapolsky describes how, as a youngster, he had "primate pictures up all over the place" [p. 21]; the computer scientist Jaron Lanier vividly describes an elaborate haunted house that he constructed at the age of eleven [pp. 114-5]. Personal workshops, laboratories, and craft decorations recalled from childhood figure in at least several of the interviews found in other sources–e.g., books such as the *Candid Science* series [cf. 8]. Indeed, this sort of attention to setting as an intellectual stimulus seems to be a recurring theme in the lives of adult professionals as well. As Csikszentmihalyi writes, based on his interviews with creative individuals in a wide variety of professions: "[I]n the last analysis, what sets creative individuals apart is that regardless of whether the conditions in which they find themselves are luxurious or miserable, they manage to give their surroundings a personal pattern that echoes the rhythm of their thoughts and habits of action." [4, pp.127-8]

Again, the evidence that "setting matters" in education is anecdotal; each biographical anecdote has its own idiosyncratic features; and undoubtedly not all adult scientists could recall such inspirational anecdotes. Still, the anecdotes are numerous enough to suggest that educational technologists ought to question their traditional focus on the constricted terrain of desktop technology. Environmental aesthetics–the way a child arranges, ornaments, and inhabits his or her own physical space–has historically been a theme that is implicitly suppressed by the limited affordances of a monitor screen. A desktop computer, after all, looks much the same after five years of use as it did when it was first unpacked; and most of the student's educational work likewise remains hidden and invisible in the form of files (with the occasional printed-out picture or document to break the monotony).

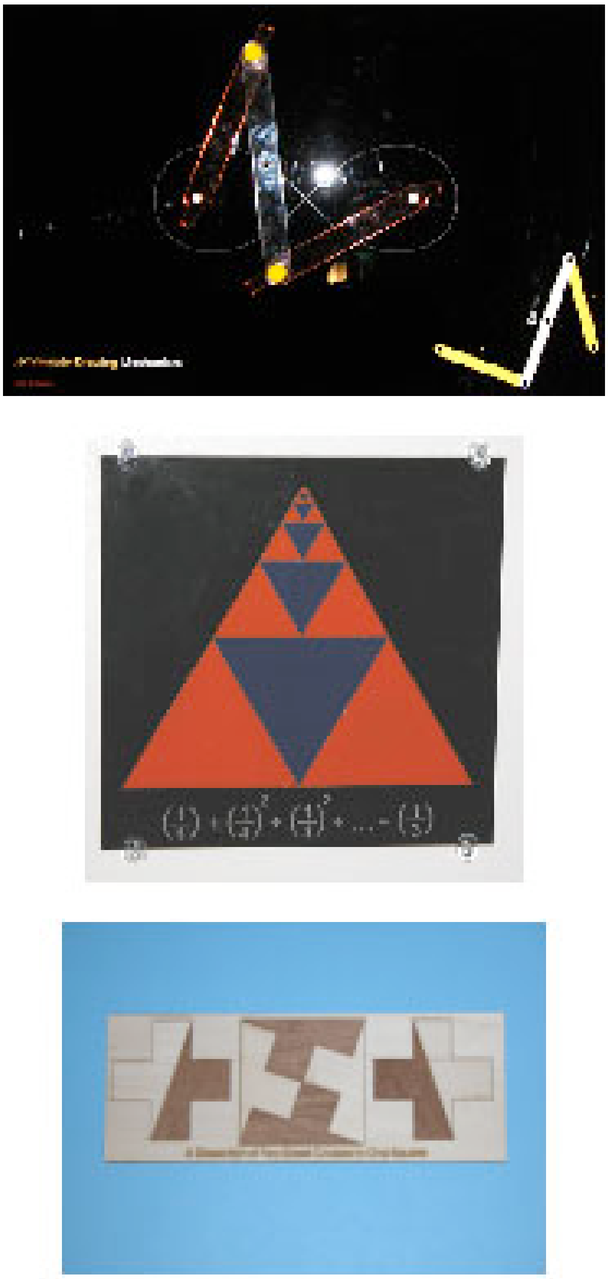

Figure 1. Three laser-cut mathematical displays. At top, an acrylic linkage demonstrates how to draw a lemniscate. At center, a "proof without words" [11] in acrylic. At bottom, a wooden display of a geometric dissection producing a square from two Greek crosses.

Fabricated objects can change educational settings, enabling those settings to evolve with children's (or, in some cases, teachers') interests and skills. Even traditional educational graphics or displays can be re-imagined with the aid of these new devices. Consider, for instance, the objects shown in Figure 1: the first is a mathematical linkage produced in acrylic, the second a "proof without words" rendered in multicolor acrylic, and the third a geometric dissection produced in wood. These were made in our lab with a (not terribly expensive) desktop laser cutter that slices the requisite pieces from wood or plastic slabs with high precision.

Naturally, all of the Figure 1 artifacts are "traditional" educational displays that could be represented on paper; but the use of materials such as wood and plastic to render these displays makes them permanent, sturdy, and, somehow, "real" in a way that a simple printed-out graphic could never be. The fact that we can print out, for instance, pieces for a brightly-colored plastic display means that educational settings can begin to take on the values of a homemade science museum, or personalized "cabinet of curiosities". In settings of this sort, artifacts are simultaneously intellectual and aesthetic creations; and they are meant to serve as physical springboards for creative conversation.

In short, then, personalized fabrication not only permits but encourages the treatment of educational settings as "ornamentable", evolving aesthetic spaces. High-quality, beautiful physical objects act as an ongoing, stimulating background against which intellectual growth can take place. By contrast, screen-based artifacts (whether on a desktop or handheld device) simply don't function seamlessly in such a capacity: they tend to belong to the *computer*, rather than the *setting* as a whole. This distinction is manifested in myriad subtle ways. It is difficult for several people to gather around (and chat about) a screen artifact; one cannot hand it from person to person, display it as an element in a growing collection, place it within an aquarium or terrarium, hang it from the ceiling, and so forth.

B. Construction as Personal Expression

Historically, construction activities in education have often been a matter of "following recipes". A student who wished to make (e.g.) a wooden machine, a paper polyhedron, or a pop-up card might purchase kits or (for the latter two examples) books of cut-out forms, but she could hardly encounter these crafts in the role of an original, creative practitioner.

The advent of computer-controlled fabrication tools now makes it possible for students to work with design software and thus to create novel, never-before-seen constructions where formerly they could only recreate existing designs. What this means is that educational fabrication is not, by its nature, merely an exercise in imitating the work of others, but is rather an unusually powerful opportunity for students to create unique, personally meaningful objects.

In our lab, we have created design software tools for a variety of construction crafts; our central purpose in building these tools is to transform "recipe-following" tasks into design tasks in just the way alluded to above. Figure 2 shows three original student-made creations: a wooden automaton, a polyhedral paper sculpture, and a pop-up card. All three were designed with the aid of software created in our lab; but in every case, the construction was conceived and designed by the student (and then realized with the aid of the laser cutter and color printer).

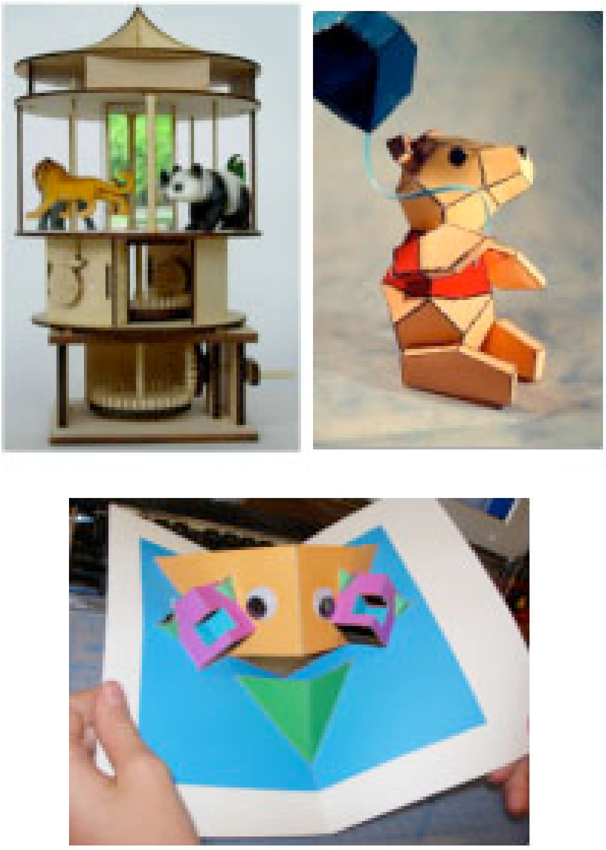

Figure 2. Three student-built craft constructions. At top left, a working wooden model of a carousel (the plastic animals were purchased, while the mechanical elements were student-designed and printed). At top right, a paper model of a bear. At bottom, a student-designed pop-up card. [2, 6, 9]

One other dimension of this theme of personal expression deserves mention here, as it will reappear in the discussion of sample scenarios in the following section: namely, the way in which opportunities for personal design and creation can potentially dovetail with day-to-day elements of children's culture. It is not infrequently the case that children might wish to design or customize artifacts such as clothing, prized objects (e.g., cell phones), desk accessories, and the like. Figure 3 shows an example of this sort of use of fabrication, created in our lab: here, a simple program takes as input a file depicting a particular shape (in HPGL format) and generates a collection of randomly scaled, translated, and rotated versions of that shape (the parameter ranges for these transformations are preset by the user). The resulting output file can be output to a laser cutter; in the case of the bag in Figure 3, a "randomized" pattern of flowers was cut out of wool felt, and a pink backing fabric shows through the cut-out regions. Again, the purpose of this example is to suggest how an opportunity for personalized fabrication can be naturally employed for the sorts of customization that young people might well find motivating.

Figure 3. A bag whose flower decoration was produced by cutting a randomized pattern of flower-like shapes into dark wool felt; the pink color derives from the pink backing fabric behind the felt.

C. Construction as Intellectual Approach

The two themes already discussed in this section focus on the aesthetic and expressive sides of construction. From the standpoint of scientific and mathematical education (and arguably, education in other disciplines as well), the "constructive stance" has merit on intellectual grounds as well (cf. [14] for an eloquent description of "constructionism" along these lines). One way of understanding (e.g.) galaxy formation, the shapes of clouds, the formation of riverbeds, the behavior of ecosystems, and many other phenomena in the world, is to try to model or simulate those phenomena. In effect, this is a synthetic approach to learning that has blossomed with the advent of computers–often, the "construction" in question is a program or simulation. The task of *designing* (e.g.) an animal suited for a particular ecosystem presents a distinct and complementary challenge to that of (say) analyzing the population of an existing ecosystem. To pursue the biological example: a student may have to consider issues or trade-offs (e.g., between resources spent in the interest of longevity versus those spent for reproduction) as a designer that would never have emerged otherwise. Moreover, the pedagogical style associated with the constructionist viewpoint is more exploratory and (at its best) self-directed than that associated with the more traditional model of "information transfer between teacher and student". Resnick *et al.* [15] express this idea eloquently:

> [U]npredictability is characteristic of constructional design. Developers of design-oriented learning environments need to adopt a relaxed sense of "control." Educational designers cannot (and should not) control exactly what (or when or how) students will learn. The point is not to make a precise blueprint. Rather, practitioners of constructional design can only create "spaces" of possible activities and experiences. What we can do as constructional designers is to try to make those spaces dense with personal and epistemological connections–making it more likely for learners to find regions that are both engaging and intellectually interesting.

Physical fabrication enriches a software-based constructionist approach still further: rather than creating purely virtual models, it is increasingly possible to create physical models of complex phenomena as well. Machines (like the one shown in Figure 2) can be interpreted as working models of notions such as mechanical advantage, oscillation, or feedback. Figure 4 shows an example in a similar spirit: the figure shows a tree model designed in a program created in our lab and fabricated on a 3D printer. A much more thorough discussion of the program may be found in [1], but for our purposes here the essential point is that fabrication increasingly allows us to combine computational simulations with tangible output. The resulting combination has, in our view, tremendous educational potential, allowing students to create sophisticated displays, working demonstrations, and scientific apparatus.

Figure 4. A plaster model of a tree, originally designed on the computer screen and then output to a 3D printer. [1]

III. TOWARD PERVASIVE EDUCATIONAL FABRICATION: A VISION OF WHAT FABRICATION COULD LOOK LIKE

The previous section of this paper presented a variety of projects within our laboratory as illustrations of central, recurring themes in educational fabrication: construction as ornamentation, as personal expression, and as intellectual approach. In this section we use these three themes to suggest scenarios for the notion of pervasive educational fabrication.

Before proceeding, we should pause to acknowledge a certain apparent tension between the "cultures" of fabrication and pervasive computing. On the one hand, fabrication is often associated with rather bulky, power-intensive machines–and although these machines are far more accessible than before, some of the more prominent fabrication devices (such as 3D printers) are still expensive. The culture of pervasive computing, however, emphasizes values such as portability, compact size, seamless integration into a variety of settings, and so forth. How are the values of these two disparate cultures to be reconciled?

Our belief is that there are, in fact, opportunities for productive detente between these two cultures. Indeed, in our view, one of the primary research challenges for each of these two cultures should be how to appropriate the advantages of the other. For the fabrication community, then, the goal is to provide students with frequent, highly accessible, and inexpensive opportunities for fabrication at a wide variety of scales, ranging from the "quick-and-dirty" small-scale construction of simple objects to the highly precise larger-scale industrial-strength fabrication of complex artifacts in specialized materials. For the pervasive computing community, the goal is to integrate the values of pervasive computing with the powerful aesthetic and intellectual advantages of physical materials.

In the short- to medium-term, this integration of cultures could plausibly take several forms. First, we argue that over time, commercial "fabrication centers" can become as plentiful and accessible as printing-and-copying centers are now. Indeed, copying centers arguably already form the foundation of fabrication sites: many such stores include high quality color printing, poster-sized printers, and other output devices that are beyond the reach of most individual users. It is a short step to imagine that these sites could also include laser cutters, 3D printers, milling machines, and so forth. The customer might then bring in (or send in via email) a file for an object to print in the morning, and pick up the physical model in the afternoon. Such centers would probably not replace the existing high-end fabrication services that already exist, but would rather become the relatively populous "low-end" versions of those industrial services.

Still another possibility would be that smaller-scale special-purpose fabrication devices would exist in the context of (say) science museums or theme parks. (In a couple of the imagined scenarios outlined below, this would be a plausible approach.) The idea here would be that a fabrication device is limited to producing variations of some particular type of object or geometry, and thus could be endowed with a relatively simple interface and could be engineered with an eye toward high speed and low cost.

Finally, it should be possible (in the somewhat longer-term) to engineer smaller-scale, more portable fabrication devices, whose relationship to the current crop of devices would resemble that between the handheld computer and the desktop machine. This would involve an intensive effort in creative engineering, but a couple of possibilities along these lines are sketched below.

In the light of these observations, then, one might imagine a variety of scenarios for pervasive educational fabrication–scenarios that connect the themes of ornamentation, expression, and intellectual approach to pervasive computing. In the remainder of this section, we take each of these three themes in turn, and explore ways in which those themes could inform a move toward fabrication in the world of pervasive computing

Pervasive Fabrication for Ornamentation. One way to accelerate the dissemination of fabrication into untried environments is to re-imagine fabrication devices that are tailored for particular ornamental purposes, or for use in particular settings. For example, fabrication tools might be designed for use in conjunction with museum exhibits and activities. A scenario emphasizing ornamentation in such a setting might take the form of a large-scale diorama in which children can individually fabricate elements for inclusion. One might thus imagine a "forest" diorama in a science museum in which children can design and print out their own trees (along the lines of Figure 4 above) to be inserted in the exhibit. Over time, the forest scene would grow with the contributions of young visitors.

A similar scenario might have (say) a model railroad layout whose background ornamentation grows and changes over time as visitors print out new things to add; or a fanciful zoo exhibit in which children design and print new (possibly imaginary) animal models to include in the exhibit.

In these scenarios, the implementation of pervasive fabrication would likely focus on creating devices that could fabricate a limited genre of objects (e.g., model animals) with an emphasis on high speed and low cost. Just to pursue this particular example, one might imagine a 3D prototyper in which some additional speed is provided by having separate units print (e.g.) the trunk, limbs, and head of a model animal in parallel, producing pieces which could then be assembled "offline" by the student designer. In other words, because the overall structure of the object-to-be-printed is known in advance and is relatively modular, the printing device can be optimized for producing structures of just that type. A location-specific sacrifice of generality can thus be used in the interest of increased speed (which is a recurring problematic factor for 3D printers).

Yet another way in which location-specific fabrication might be optimized in this sort of scenario would be to separate the "design" and "object retrieval" elements of the device. Typically, when one designs an object for fabrication, the computer screen on which the object is modeled is positioned near the printing device itself. Indeed, this arrangement is generally preferred to the alternative in which printing devices are separated (e.g., in their own designated room) from the computers that employ them. In a museum setting, however, one could imagine a scenario in which children design (say) an animal upon entrance to an exhibit, and then somewhat later arrive at the point where the printed-out animal is retrieved and inserted into a diorama. This would be one way of (partially) finessing the slow printing speed of 3D prototypers by making use of the structure of the particular public environment in which they are incorporated.

Pervasive Fabrication for Personal Expression. There are a number of potential opportunities for children to create and fabricate small-scale objects that would be personally meaningful to them, rather than purchasing pre-manufactured items. Many of these opportunities have a rather homespun feel, appropriate to events in children's culture. For instance, youngsters might be able to design and print party favors that are individualized souvenirs. Another possibility is that children might fabricate small accessories such as costume elements (their own eyes, teeth, horns, etc.) for Halloween; or their own specialized jewelry; or personalized baubles for a holiday tree; or customized objects for backyard treasure hunts. Here, the emphasis would be on providing inexpensive small-scale opportunities for quick fabrication in the home or local neighborhood. A potential strength of this approach is that it lends itself well to venerable children's traditions (of holidays, of improvised games) that often elude the attention of adults, but that nonetheless lend creative inspiration to children's lives. (Cf. the indispensable reference on these juvenile traditions by Iona and Peter Opie. [13])

There is something of a pre-existing commercial tradition of "children's fabrication" along these lines, exemplified by the once-popular line of "Thingmaker" toys that permitted children to bake plastic models of (e.g.) bugs or dragons in pre-supplied molds. These toys were geared toward the sort of children's traditions–creating costume elements, jewelry, and so forth–alluded to in the paragraph above. Still, as discussed in the previous section, these toys constrained children to produce only a fixed set of items: that is, the child could not produce her own custom-made mold.

The obvious advantage of fabrication devices for this sort of children's activity is precisely, then, the opportunity for children to engage in design as well as physical manufacture. These sorts of examples suggest yet another way in which fabrication, when tailored toward a fairly specialized genre, could be made more pervasive: namely, through the design of fabrication devices for very small objects (of perhaps 10 grams or less). Re-imagining prototypers or milling devices for such small objects might facilitate both the speed and accessibility (low materials cost) of children's fabrication.

Pervasive Fabrication as Intellectual Style. A central goal of pervasive fabrication should be to expand the opportunities for "learning by construction" into a far broader range of physical settings. One might explore, for instance, the possibility of creating "portable scanners" for children (and amateur scientists generally), along the lines of the current laboratory devices. The basic idea would be that a student who encountered (say) an interesting small object–a pine cone, a flower, a cocoon, even perhaps an insect–could place the object in her portable scanner and read its shape, obtaining a file that could then be taken to a fabrication center and printed in physical form. In a sense, one might view such a scanner as analogous to a portable camera, except that its purpose would be to operate in conjunction with fabrication devices. Such a capability could lead to a much more powerful form of "nature scrapbooking" in which children could not only record observations about the world, but could recreate, study, and custom-design their own models of various natural objects and phenomena.

The analogy with a portable camera is a fertile one, and worth pursuing just a bit more. Just as a portable digital camera is seen as an easily portable device that can communicate with desktop printers (to produce high quality hard-copy photographs), one could likewise imagine the portable scanner as an affordable device to communicate with 3D printers. Indeed, one might imagine the portable 3D scanner as something that could be compatible with a cell phone, in much the same way that phones now directly incorporate cameras; this would allow users to directly send a scanned form via phonemail to a remote printer. Thus–just to elaborate on the scenario of the previous paragraph–a child on a nature walk could place an interesting beetle inside her portable scanner; send the scanned form directly to a printer at home (or at some printing center); and later during the day retrieve a physical model of the insect that she observed.

These scenarios for pervasive fabrication are, we believe, entirely plausible. At the same time, they are only initial suggestions of what might be possible should the cultures of fabrication and pervasive computing truly merge. Indeed, there are still other lenses through which to view this merger: perhaps one could see the proliferation of student-designed and computer-generated artifacts as representing a spread of "computational thinking" into children's worlds. As children create (e.g.) three-dimensional fractals or recursive objects for display (as in Figure 4), or objects that incorporate degrees of randomness (as in Figure 3), or objects whose dynamic behavior is modeled by computer before being rendered in physical materials (as in the popup card in Figure 2), they are seeding their environments with lovely but profound exemplars of computational ideas and processes. Thus, if one of the goals of pervasive educational computing is to promote the spread of computational ideas amid day-to-day settings, then practitioners in the field should consider, and exploit, the affordances of personal fabrication for that purpose.

More generally, a merger between pervasive and constructive educational computing would go a long way toward making creative design more universal and democratic. Children need opportunities to develop their ideas through both the virtual media of "purely" computational processes and through working with an ever-widening landscape of physical materials. Pervasive learning is an enterprise that, at its best, can engage children through their eyes, minds, and hands; and just as these elements are interwoven within human beings to marvelous effect, they can likewise be interwoven in our educational designs

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