The Homespun Museum: Computers, Fabrication, and the Design of Personalized Exhibits

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ABSTRACT

The traditional view of the "home computer" is as a self-contained appliance: computation, on this view, is something that takes place within a desktop box, and that produces interesting visual effects only on a screen. In this paper, we argue that one can alternatively view "the computer" through its tangible effects on larger settings: that is, the computer can be imagined as the heart of a creative workshop centered within the home or classroom. The advent of accessible fabrication devices, as well as small computers that can be embedded in craft items, permits users to think of the room at large as a place in which computationally-enriched or computationally-designed "exhibits" of various types may be displayed. We illustrate this idea with a variety of projects undertaken within our laboratory.

Author Keywords

Computational crafts, fabrication devices, embedded computation.

ACM Classification Keywords

H5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

INTRODUCTION

The notion of a "home computer" is, in historical terms, a recent one; computers have been in homes for about thirty years. Within that short time, it has been something of a triumph for computers to become "mere appliances", as opposed to daunting scientific or business instruments. In the view of the home computer owner, there is a natural and largely unconscious analogy between computers and other personal devices: the computer is, in its way, just like the television, or CD player, or washing machine.

Thinking of the computer as an appliance represents an advance: appliances are, after all, familiar and unfrightening things. On the other hand, there are profound and generally unexplored limitations to this view: the computer is relegated to being a desktop device, placed in its own local spot within the room, and confined to that location. In this mental image, the remainder of the room is largely unchanged: the computer's "reach" into the space itself is localized to the desktop. Our imagined room is (in the most extreme case) filled with consumer items; and the computer is just another thing that we own.

In this paper, we argue that these traditional images of "home computation" are dated and constraining. We believe that the computer can be thought of not merely as a desktop appliance, but as the central element of a workshop: a device that guides the fabrication of expressive and personalized objects that can be placed all around the room (or classroom). The advent of newly accessible fabrication devices and materials, as well as the use of embedded computational media, permit us to treat computers as partners in a newly revived tradition of home crafting. Moreover, these recent technological advances permit us to rethink our physical spaces as sites in which we can display a remarkably wide range of creative work. Much as the first high-quality laser printers democratized the practice of writing, bringing the aesthetics of professional typesetting to the individual user, these technologies may well democratize the practice of home decoration. Computational media, through the medium of computationally-enriched crafts, allow us to make our physical spaces increasingly expressive, idiosyncratic, and beautiful.

The remainder of this paper seeks to expand upon this theme, drawing on examples of "computational craftwork" from our laboratory at the University of Colorado. These projects are meant to illustrate and explore the ways in which users–and in particular, children–can blend the affordances of computational tools with both new and old techniques of crafting and construction. By viewing computers as craft devices, as shop controllers, we also seek to diffuse the idea of "human-computer interface" beyond the confines of the screen. In particular, the room itself–whether, e.g., a child's bedroom, a classroom, or a study–can be thought of as the focal object of the software designer's imagination. That is, rather than think about how software alone should be designed, our preference is to think about what sorts of

C&C'05, April 12-15, 2005, London, United Kingdom.

objects and personalized exhibits a user might wish to create, what sort of room he or she might wish to build over time. With this in mind, the software designer becomes a craft-activity-designer: and in this context, desktop software is itself just one element in the larger project of helping the user to create their own environment.

The second section introduces two fundamental avenues through which computationally-designed and computationally-enriched objects may be created: namely, the use of novel fabrication devices and the use of programmable craft objects. These two themes are not at all mutually exclusive: indeed, as we will argue, the various new tools and techniques of craft construction can be productively combined and integrated. Still, for the sake of structuring our examples, it is reasonable to separate these two themes for the time being. Moreover, in discussing these themes of home fabrication and programmable objects, we will illustrate their application through a variety of sample projects. The third section of this paper is more speculative in nature: here, we use the sample projects of the second section as springboards for discussing several ways in which homes and classrooms could begin to evolve into personalized "exhibit spaces". In the fourth and final section, we discuss the relationships between our own work and that of researchers in related areas; and we describe a number of fertile areas for ongoing research and development in the general area of computational crafts.

THE NEXT GENERATION OF CRAFT OBJECTS: FABRICATION AND EMBEDDED COMPUTATION

Much of the newly expanding power of computational craftwork derives from the fact that home and school users are increasingly able to design and "print" new types of objects through the use of fabrication devices. The result is that numerous types of objects that were hitherto beyond the conception, skills, or budgets of such users are now constructible. A second source of expanded power lies in the behaviors of craft creations themselves: it is now possible to work with materials, or "kits" of pieces, that can be programmed by the user to behave in interesting, complex, or unexpected ways. In this section, we describe and illustrate each of these notions in turn.

It is also perhaps worth mentioning–before proceeding to a more specific discussion of techniques and projects–that many of our ideas and examples are derived from an interest in furthering mathematics and science education. We believe that students in these disciplines benefit when they can create objects that have not only aesthetic appeal but also a connection to mathematical or scientific content. With this in mind, the reader will note that many of our craft examples are the sorts of things that might well show up in a mathematical artwork exhibit or science museum: polyhedra, surface models, dynamical systems displays, and so forth. In fact, we argue that the notion of computational craftwork is particularly suited for the creation of educational displays (there will be more to say about this in later sections). Nonetheless, the adventurous reader may wish to view our examples with an eye toward applying the basic techniques and approaches of computational crafting toward other disciplines–e.g., making architectural models, or model railroad layouts, or holiday decorations, or mobiles, or marionettes, or indeed a myriad other possible domains.

Fabrication: The Redefinition of the Printer

The analogy suggested by the title of this subsection is, we believe, a fertile one. Rather than thinking of "printing" as solely a matter of applying ink to paper (rich as the possibilities in that medium might be), we can expand the idea to encompass "printing out" three-dimensional items in wood, acrylic, foam core, wax, plaster, and numerous other materials. This in turn augments the range of projects and techniques available to children and crafters.

Laser Cutters

Perhaps the most accessible and straightforward of the recent spate of fabrication devices is the laser cutter. Essentially, laser cutters work much like line plotters: while line plotters move a pen over a stationary sheet of paper, laser cutters move a laser beam over a sheet of material to be cut. Materials that can be used in such devices include sheets of wood (such as basswood, balsa, and walnut); acrylic plastics; and cardboard.

Figure 1. A geometric dissection display realized in laser-cut wood.

Figure 2. A "proof without words" in wood.

Figures 1 and 2 show relatively simple examples of the sorts of displays that can be made with a laser cutter. As is often the case with our examples, the intent is to show the sort of mathematical display that might be a typical item in a science museum exhibit. Figure 1 uses two different types of wood (basswood and cherry) to illustrate a geometric dissection in which two Greek crosses may be combined to form a square. Figure 2 (created by S. Nicolo in our lab) depicts a "proof without words" using stained wood pieces mounted in heavy cardstock. (The proof itself is taken from the front cover of a marvelous compilation of such proofs. [11]) The central set of triangles clearly constitutes one third of the picture; by summing the areas of the individual light triangles, the mathematical equation represented by the picture thus can be written:

$1/4 + (1/4)^2 + (1/4)^3 + (1/4)^4 + ... = 1/3$

Both Figures 1 and 2 thus use wood in a purely pictorial fashion. Conceivably, of course, these mathematical ideas could be displayed on paper; but the choice of wood lends both items the sort of permanence and dignity associated with more professional exhibits (a point that we will return to later).

Figure 3. A "sliceform" ellipsoid constructed from a set of slotted wooden pieces. (Cf. [3], p. 157.)

Figure 3 shows an example of a different sort of mathematical craft available to the laser cutter user. Here, a three dimensional "sliceform" model of a surface has been constructed by printing out a set of slotted pieces in wood, half with slots going from the top of the piece to the center, and half with slots going from the bottom of the piece to the center. Once a complete set of these pieces has been printed, the individual pieces may be joined via their slots (the "top-slot" pieces at right angles to the "bottom-slot" pieces). One remarkable (though too short) book on such models [16] depicts paper constructions, but again the use of wood or acrylic lends these mathematical items heft, unusual beauty, and permanence. In our lab, we are currently developing a software tool that will permit users to view a model of a surface on the computer screen and to subsequently print out a set of wooden or plastic pieces that can be used to assemble the shape in the manner of Figure 3.

Figure 4. A mechanical sea monster automaton; the foam core monster, cams, and box structure were printed on a laser cutter.

The laser cutter enables crafters to "print out" still other types of items, including mechanical elements such as cams or gears. Figure 4 shows a mechanical sea monster whose various pieces have been printed out in foam core and wood: when the crank is turned, the sea monster appears to undulate. The cams that animate this sea monster were in fact designed in the "MachineShop" program under development by G. Blauvelt in our lab.[1, 2] The basic purpose of this design application is to permit students to create playful mechanical automata featuring elements such as gears, cams, and levers, much along the lines of the fascinating examples of London's Cabaret Mechanical Theatre artists.[W1] Here, the use of wood (rather than, say, paper) as a medium of construction is a much more motivated choice than in the previous examples. There are, in fact, paper construction kits for mechanical toys available to children [see, for instance, W1], but such kits are often difficult to construct and fragile once completed. (Consider the difference in sturdiness and reliability between a gear train rendered in paper and one rendered in wood.) Moreover, the kits do not permit children to design their own never-before-seen automata; rather, they are simply construction sets for one particular automaton. The use of the laser cutter as "printer" (in combination with a design application such as MachineShop) thus enables students to create original and mechanically robust constructions.

Figure 5 shows still another use of the laser cutter, as a device for an unusually precise sort of papercrafting (one that would require uncanny patience and skill to accomplish by other means). Here, the laser cutter has been used to etch thousands of small holes in a sheet of construction paper to create a portrait of a dog. The holes may be thought of as pixels in a display; and in fact the holes are of varying sizes, corresponding to the grayscale value of the corresponding pixel. Thus, the portrait conveys a sense of "light" and "dark" areas strictly by means of light permitted through the holes in the paper. This example is intended as an illustration of the ways in which the laser cutter can potentially expand the range of activities even with a "traditional" children's material such as paper. The precision of the laser cutter facilitates cutting such complex patterns as (approximate) fractal curves, periodic tilings, and so forth.

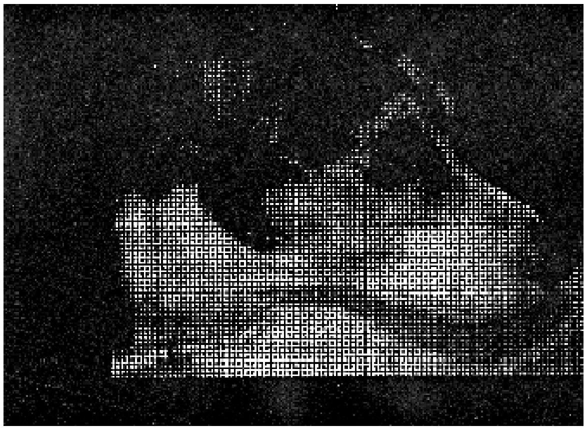

Figure 5. A portrait of a dog. The "pixels" are in fact laser-cut holes of varying sizes cut in construction paper.

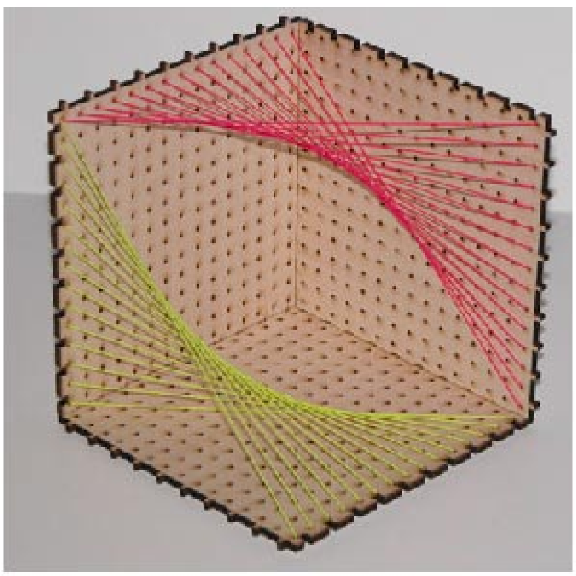

Figure 6. A mathematical string sculpture. The wooden frames anchoring the strings were printed on our laser cutter.

Figure 6 depicts still another use of the laser cutter in conjunction with a "traditional" craft material–in this instance, string. The laser cutter has been used to create interlocking frames (much in the manner of the venerable "Space Spider" toy [cf. 4]) with precision-cut holes: string may be drawn through sequences of holes to produce representations of mathematical curves and surfaces. Still other uses along these lines might be to create more complex frameworks of pieces (e.g., twelve wooden struts that comprise the edges of a cube) through which still more complex string patterns may be woven.

Figure 7. A handbag decorated with laser-cut fabric representing a mathematical function.

Finally, Figure 7 illustrates the use of the laser cutter to produce mathematical patterns in fabric. The figure shows a handbag (decorated by L. Buechley) upon which a piece of fabric in the shape of a complex function has been sewn.

Overall, then, the purpose of the preceding examples has been to suggest the extraordinary versatility of a single new device in the context of computational crafts. The following subsection presents two potentially still more powerful devices.

Three-Dimensional Printers and Milling Machines

One limitation of the laser cutter as a printing device is that it is primarily for use with flat surfaces (such as sheets of wood or cardboard). A more recent class of fabrication devices, three-dimensional printers (or prototyping machines, as they are sometimes called) can be used to produce models of complex three-dimensional shapes that would be difficult or impossible to create with a laser cutter.

Briefly, three-dimensional printing works by laying down a large number of successive cross-sections of the form to be printed. Each cross-section is printed out directly above (and contacting) the previous one. Many such printers make use of successive layers of liquid plastic substrate that are hardened as they are printed by an ultraviolet light beam; another type of printer (this is the type in our own lab) lays down thin layers of plaster, hardening each successive cross-section of powder with a liquid adhesive. The overall idea, then, is that one "prints out" an object, in whatever materials, as a succession of thin cross-sections. (A spherical ball, for example, would be created by many circular cross-sections at successive latitudes, starting from a tiny dot at the "South Pole" and growing to a great circle at the "equator" before shrinking back toward the "North Pole".)

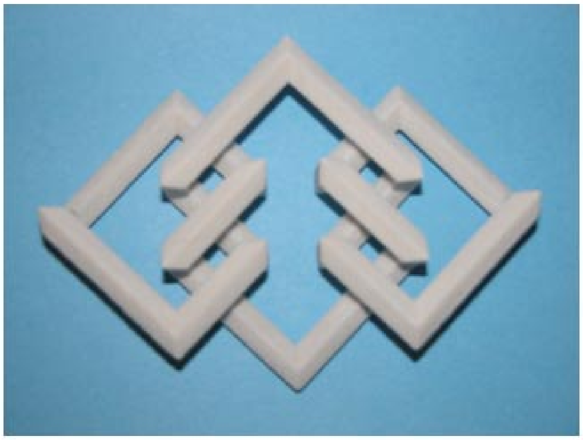

Figure 8. A closed six-crossing knot form printed in plaster.

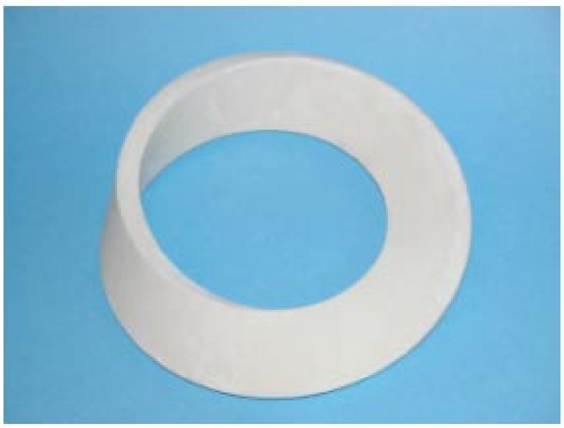

Figure 9. A printed plaster model of a Moebius strip.

Figure 10. A printed plastic recursive tree figure.

Figure 8 shows an example of a mathematical construction particularly suited to the affordances of 3D printing: here, a complex knot form has been printed out in a single piece in plaster. The software used to create this knot form is under development in our lab: the essential idea is that the user can specify a path taken by a point moving in three-dimensional space, and then "print out" that path as an object. By creating a path that ends at the same point at which it began, we can produce a closed form such as the knot in the figure. Figure 9 shows yet another unusual mathematical "printout": a model of a Moebius strip. Here, the "path" taken by the moving point turns around in a circle while twisting (much like an airplane's "roll") by 180 degrees.

Figure 10 depicts another object produced by a three-dimensional printer (although here the designer, W. Pell, used a printer other than our own to create an object in plastic). The figure shows a simple model of a tree created by a recursive graphical algorithm (those familiar with the Logo language will recognize this form as a classical turtle-drawn pattern realized in a three-dimensional model).

None of the models in Figures 8, 9, or 10 would have been a realistic classroom-level design project before the advent of three-dimensional printers. Such projects in fact approach the professional "look" of a museum exhibit–and this again emphasizes a point that we made earlier: namely, that computer-controlled fabrication is beginning to democratize physical design, to make the process less forbidding, much as laser printers and word processors democratized the process of printing professional-looking documents.

In addition to three-dimensional printers, less expensive desktop milling machines are likewise available for three-dimensional fabrication. Such devices are computer-controlled high-precision drills, and are able to carve out specified patterns from blocks of material such as plastic or wax. (The range of available materials is in fact much greater than that employed by three-dimensional printers.) A typical milling machine employs a single downward-pointed drill whose depth and placement are controlled over time by a computer program. It is possible, though not easy, to use such a device to create the Moebius strip in Figure 9: because the drill only points downward, the model has to be "turned over" in the device after its top half has been carved out from the original block so that the bottom half can likewise be carved. (We have in fact managed in just this way to create a plastic model of the Moebius strip with a recently-acquired milling machine.) On the other hand, it would not be possible to create (in one single piece) a much more complex form such as the knot of Figure 8 using a milling machine; the drill would not be able to carve away the various internal spaces within the knot's structure. We will return to some of these practical considerations in the third section of this paper.

Embedded Computers: Creating Programmable Craft Objects

The examples of the previous subsections all assumed that "exhibit items" were static, printed objects. A still more exciting possibility is that of creating displayable craft items that are dynamic and (in many instances) user-programmable. For educational purposes, this suggests that the range of phenomena illustrated by such kinetic exhibits can include (among many other possibilities) oscillations, approach to equilibrium, chaos, randomness, and even "smart" behaviors such as adaptation, learning, and interactivity with users.

Our current examples of such dynamic displays are still at a relatively early stage of development, but they suggest the likely eventual range of dynamic, programmable craft displays. One example is a set of small cubical blocks (known as "smart tiles"), created by N. Elumeze. Each block is a separate device containing its own microprocessor, multi-color LED, and touch-sensitive disk. When the blocks are placed side-by-side within an array, they communicate with their immediate neighbors in synchronized time-steps to enact programs typical of cellular automata [cf. 17], often generating remarkably complex dynamic light patterns. (For instance, one venerable automaton program is the famous "Game of Life", invented by John Conway and popularized by Martin Gardner in his Scientific American columns of the early 1970's. [5]) The "array" in which the blocks are placed is a fabric that supplies power to the blocks and allows communication between them. Importantly, any one of the blocks may be removed from the array, brought to a desktop computer, and reprogrammed through a Logo-like programming interface that we are developing. This means, in effect, that each individual block can run its own unique program. We think of the blocks as a sort of "programmable construction kit" of pieces, each of which can be customized before their combination in the array. By programming the pieces according to taste, the user can create an endless range of personalized displays.

Figures 11 and 12 show the current state of the "smart tiles" project. In Figure 11, a small set of tiles is shown running a cellular automaton program (it happens that this is the "Game of Life" program). Figure 12 shows a 10-by-10 array of the tiles (with their tops open so that the inner construction is exposed to view).

Because of the style of construction of the smart tiles, one can imagine creating dynamic cellular automaton displays and placing them at different locations throughout the room (or classroom). In fact, it is conceivable that several arrays of blocks in different locations could be arranged to communicate with each other, so that a single cellular automaton program might be running, in effect, over dispersed locations. Figure 11 hints at a still more entertaining idea: an array location needn't be occupied by a "standard" tile, but could conceivably be occupied by a tile connected to (say) a motor or audio signal. In Figure 11, one of the tiles is in fact a controller for a motor that powers a commercial mechanical toy. (Thus, when a standard tile in this location would have had its light turned on, the special motor-controlling tile turns the crank of the mechanical bird-watcher.) The simple example of Figure 11 thus hints at a much wider range of possibilities, in which complex programs running throughout the space of a room are able to produce a wide variety of visual and tangible effects.

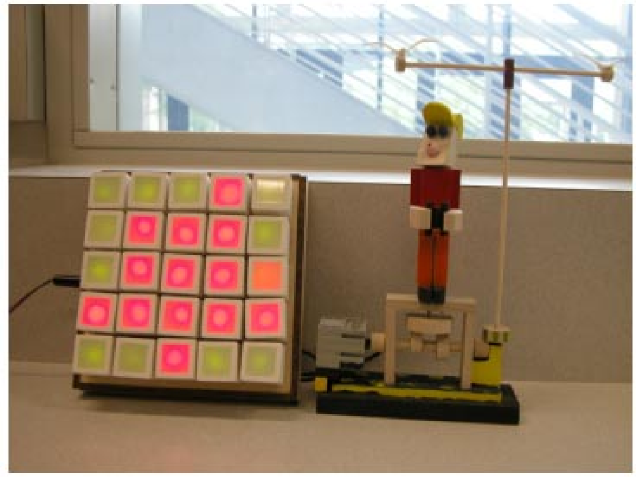

Figure 11. A set of "smart tiles" running a Game of Life automaton program. One of the tiles is connected to a commercial mechanical toy, as described in the text.

Figure 12. A ten-by-ten array of "opened" smart tiles illustrating the construction of the individual pieces.

Figures 13 and 14 show yet another programmable construction kit-in-development, this one designed by L. Buechley. Again, neighboring pieces communicate with one another over time to change their states, much as in a cellular automaton: but here, the pieces are triangular prisms, and they may be rearranged into all sorts of three-dimensional physical structures before running their desired program. A single dedicated piece is connected to a desktop machine (the connection is visible toward the bottom right of Figure 13), which supplies power and a timing signal to the overall construction.

The "crystal cellular automaton" (as we have come to call this system) is thus customizable, at least in principle, in two distinct ways: pieces may be individually programmed, and, once programmed, those pieces may be arranged into a multitude of physical structures, much like building blocks.

(In the project's current state, the programming interface is still primitive; programming the prism blocks would be prohibitively difficult for most users.)

Figure 13. A set of triangular prism pieces. The piece connected to the desktop machine can be seen toward the bottom right.

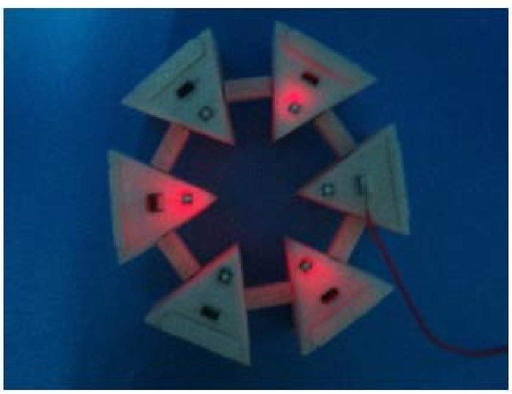

Figure 14. A rearranged set of triangular prisms, running a cellular automaton program.

COMPUTATIONAL CRAFTS: TOWARD THE PERSONALIZED EXHIBIT

The previous section described a variety of sample projects that make use of two central themes of computational crafting: the exploitation of personal fabrication devices, and the use of embedded computers to endow "kits" of materials with programmable behaviors. In this section we return to the topic of the introduction–namely, the ways in which computational crafting can eventually impact (or more accurately, can help people to impact for themselves) the design of home and classroom spaces.

What would it be like to live in a culture permeated by devices and techniques of advanced personal design? One conceivable shift might be that the barriers (of cost, of specialized skills, of time) to creation would be lowered sufficiently so that many more individuals would develop their own idiosyncratic collections of created objects. We have found, in our own lab, a distinct pleasure in watching our collection of mathematical and scientific items grow over time; and our own space has come to take on a look not entirely unlike that of a personalized museum. It is this analogy, and its steadily increasing aptness in the analysis of our own space, that has suggested to us the possibilities of an increasing diffusion of "museum values" into personal spaces.

In fact, it may be more accurate to speak of a return to "museum values" rather than to think of this shift as completely novel or unprecedented. The precursors to modern public museums were, in fact, private collections– "cabinets of curiosities" maintained by (necessarily wealthy) individuals. In some cases these collections focused on artworks; in others, scientific hobbies or natural specimens; in still others, there was a marvelous eclecticism to the styles and sources of the various objects. By and large, the purpose of these collections was to provide entertainment and a spur to enlightened conversation among visitors. (See [10] for an informative and sumptuous history of this tradition.)

A return to "personalized exhibits" might therefore, in one sense, bring museum culture back to its origins in private homes as opposed to large public institutions–but with several crucial differences. First, the development of such personalized collections would hardly require the massive wealth of the original cabinets of curiosities; ideally, the barriers to creating a 21st century cabinet would be creative rather than financial. Second, the sort of collection envisioned here would largely consist of self-created or customized objects (rather than, e.g., exotic and priceless rarities, whose natural home would still be a public museum space). A corollary of the personalization of these collections would likely be that they would have much more emotional resonance–much more sentimental meaning and value–for their owners/creators. Nonetheless, it is possible (at least if we allow ourselves to think optimistically for a moment) that the values of such collections as true "conversation pieces"– as sparks to exploratory discussions–would still be retained from the earlier culture of personalized collections.

Thinking at a smaller and less ambitious scale, we believe that the techniques described here, and that computational crafting in general, are likely to work a pervasive long-term shift in the decoration of classrooms and school environments. Such environments already have something of the flavor of homespun exhibits: teachers will often post students' written work on the wall, or place student constructions on shelves. (It would be no surprise in a mathematics classroom, for instance, to see the occasional student-constructed polyhedron or origami figure on display.) Thus, the advance of computational crafting can capitalize on an existing culture of classroom display; but it can lend that culture a markedly more creative and expressive tone. Through the use of fabrication devices, students can construct (say) elaborate dioramas, or miniature historical sites, or mechanical devices, or science project displays; through the use of embedded computation, those artifacts can be made to move, change color, make sounds, or respond interactively. The pedagogical goal of such displays may come much more to approximate the goal of the earlier cabinets of curiosities: classroom displays can increasingly become springboards for conversation and personal reflection and growth.

Obstacles and Challenges

The skeptical reader might well argue that our admittedly optimistic view of the growth and effects of computational crafting is misplaced. After all, there are plausible reasons to believe that either (a) the phenomenon of computationally-enriched craftwork will forever be a minor and unimportant one, practiced (if at all) by a very tiny minority, or that (b) should the practice of computationally-enriched craftwork expand, the effects of this expansion (on education, for example) may not be benign. These are arguments worthy of much more vigorous discussion, but in the remainder of this section we try to address several of the major areas of debate.

First, it is often objected that the cost of (e.g.) fabrication devices or embedded computers makes the practice of computational crafting prohibitively expensive. Our own response is that the materials and devices discussed in this paper would represent major investments for most schools; but even now, they are at least within reach of many school budgets. A rough approximation, corroborated by a search of commercial websites, would put the cost of a milling machine at about $7K, the cost of a desktop laser cutter at about $17K, and the cost of a three-dimensional printer at about $35K. Certainly these are not inexpensive items, but they are at least comparable in price to many other laboratory purchases. Moreover, by analogy with other commercial technologies–computers, color printers, and memory storage, to name a few–there is good reason to believe that the cost of the technologies described in this paper will decline (if not plummet) during the next decade, to the point where a laboratory fabrication station would be within the price range of most high schools.

Conceivably, the fabrication devices described here might also be made available through neighborhood "printing centers" (which indeed might represent the future of today's commercial copying and printing centers). That is, one might go to the same store to print out a thousand pamphlets, a few large laminated posters, or a single plaster Moebius strip, all specified on a single portable disk. A commercial infrastructure of printing/fabrication centers might also serve to address a second objection to our optimistic view–namely, that the sorts of craft activities that we envision present safety risks. There are, in fact, some safety concerns with the technologies discussed here (particularly in the realm of fabrication): laser cutters employ powerful laser beams, for example, and cannot be used with inappropriate materials (some plastics give off noxious fumes, and some surfaces–notably metals–reflect back too much of the incoming beam). Likewise, in the case of our own plaster-based three-dimensional printer, it is necessary to treat models with an organic solvent after removal from the printer; the treatment process hardens the plaster and needs to be performed with care and in a well-ventilated area (we use a chemical hood). Again, our belief–based on recent history with other commercial technologies–is that the next generation of fabrication devices will be far simpler (and markedly safer) to use, so that students could make use of them without oppressive adult supervision. Commercial printing centers could still be available for the more expensive or skill-intensive methods of fabrication.

Finally, it might be argued that there is something lost in the very nature of craftwork when computers are employed in the design or printing process. Along these lines, a mathematical display (such as the one in Figure 1) created by hand is more valuable than one printed on a laser cutter; or a hand-carved knot form is more valuable than one printed in plaster.

Arguing this point touches on some profound issues related to the nature of creativity. We believe that there is indeed a delicate interaction, in every craft activity, between human design skills (realized both in the mind and the hands) and technological affordances. We can't pretend to know where the proper balance lies for each and every activity, though it should be pointed out that such materials as paper, string, paints and dyes, woodworking tools, and so on are no more or less "technological" than the materials that we have discussed here. Indeed, most traditional crafters rely on a technological infrastructure to support their activities: an origami expert is not usually involved in the production of paper, nor do most woodworkers create their own drills and lathes. Perhaps it is more profitable, ultimately, to analyze craft activities in terms of their realization of individual, provocative, and unique human ideas rather than their dependence on (or independence from) particular technologies.

RELATED AND ONGOING WORK; POTENTIAL AVENUES FOR FUTURE WORK

The projects described in this paper have been greatly influenced by work in several traditions. The most direct influence is the work of Mitchel Resnick and his colleagues at the MIT Media Lab in developing the programmable Lego brick (or "cricket") and more generally in combining programmability and computation with physical artifacts for mathematics education (what Resnick calls "digital manipulatives").[13, 14] There is also a blossoming interest in weaving computation into physical spaces for educational purposes, exemplified by the work of Yvonne Rogers at the University of Indiana [15]. The work of Hiroshi Ishii and his colleagues (again at the Media Lab) is for the most part less directly educational in intent (and has less direct interest in programmability per se) but also illustrates an astonishing variety of ways in which computation may be "spread through the room", a motivating theme of computational craftwork.[7] Work on blending computation with construction kits is likewise an interest of Ishii's research group [6, 12] and creative efforts in computational "building blocks" are described in [8, 18].

Collectively, these efforts share many of our own interests, particularly in the area of blending physical and computational media for educational purposes. The distinguishing characteristic of the work described here is in the way that it grows from a tradition of craft activities (particularly those practiced by children) with an eye toward integrating mathematics and science education into design and ornamentation.

Most of the projects described in this paper are at rather early stages of construction (MachineShop is an exception, and the first stages of user testing have recently begun). The cellular automaton construction sets, "sliceforms" designer, and path-printing (knot and Moebius strip) projects are all works-in-progress; pilot testing of the "smart tiles" construction set will begin this winter. Other examples shown here (e.g., the "proof without words") represent illustrative instances of mathematical displays, and one of our ongoing goals within our laboratory is to devise a variety of such individual displays as examples of how mathematics education, craftwork, and computational media may be integrated.

Besides this ongoing work, there are exciting directions for future work as well. As mentioned earlier, the themes of embedded computation and personal fabrication have natural areas of overlap: for instance, it is plausible that students might wish to design and print their own unique structures (e.g., cellular automaton pieces) in which to house computational elements for combination in larger "kits" and systems such as those described earlier. Or, less ambitiously, small amounts of programmable behavior might be added to craft displays (for example, a string sculpture might be placed in an oscillating frame to display a slowly changing family of string figures).

Another direction for future work is to explore in greater depth the design and aesthetics of professional museum displays (particularly those typical of science museums) with an eye toward translating that professional knowledge and tradition into home and classroom settings. Many writers have recently bemoaned the capture of children's culture by an avalanche of advertising and consumer goods (cf. [9]); we believe that by gently reviving the ancient connection between museum-like displays and personal design, it may be possible to shift children's activities less toward consumption and more toward expressive, idiosyncratic creation.

ACKNOWLEDGMENTS

We are grateful to Mark Gross, Michael Mills, Andee Rubin, Mitchel Resnick, Gerhard Fischer, Roy Pea, and Carol Strohecker for their ideas, influence, and conversation. This work was funded in part by the National Science Foundation (awards no. EIA-0326054, and REC0125363), and by a gift from Mitsubishi Electric Research Laboratories (MERL) in Cambridge, Massachusetts.

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