# As We May Print: New Directions in Output Devices and Computational Crafts for Children

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## ABSTRACT

In recent years, educational technologists and designers have begun to explore a variety of ways in which physical and computational media can be integrated—for instance, through the design of "intelligent toys" for children. This paper describes our ongoing efforts at exploring a different sort of physical-computational integration, focusing on children's design activities, output devices, and the notion of "printing out" more generally. We describe several representative systems under development in our group; each of these systems highlights particular possibilities for exploring and experimenting with output devices for children's crafts. We also present a set of design heuristics—useful techniques for those educational designers interested in expanding the range and expressiveness of craft activities for children.

## Keywords

Educational technology, computational crafts, output devices.

## INTRODUCTION

For children who are especially fortunate, the world is a treasure trove of well-designed, enticing educational artifacts—playthings, kits, materials, *stuff* that collectively illuminate mathematical or scientific ideas, or that spark curiosity and imagination. A kaleidoscope acts as an introduction to both mirrors and rotational symmetry; a terrarium to the ideas behind ecosystems; a top to the notion of angular momentum; a collection of paper polyhedra to the foundations of solid geometry. Until recently, computers have had little connection to (or impact upon) this other, "real" world of tangible educational artifacts, except in somewhat oblique or distant ways: a computer animation might (for instance) simulate a top or a kaleidoscope, but it could hardly evoke the sense of immediacy and surprise of the physical objects themselves.

This longstanding chasm between the abstract, virtual world of traditional computational media and the tangible, material world of educational artifacts is progressively vanishing in the face of a changing portrait of the "computer". Historically, a "computer" has been, by assumption, a desktop device equipped with keyboard, screen, and (more recently) Internet connection; and educational designers who wished to make use of the device naturally played to its strengths by creating screen-based tools and applications. In recent years, however, the "computer" has increasingly become more diffused into the physical environment—through embedded or ubiquitous computation, "augmented reality" systems, "smart" materials, and the like. These developments have not diminished the very real and continuing value of purely screen-based educational systems—such systems are often able to present ideas (such as frictionless worlds, objects moving at speeds close to that of light, or complex collections of intelligent agents) that are hard to represent by means of real-world objects. Nonetheless, the increasing détente between the tangible and virtual allows educational designers a far greater leeway in extending and reinterpreting the landscape of children's artifacts.

For many designers, the blending of physical and computational media takes the form of creating "intelligent toys", in which computers are embedded within physical objects (such as dolls, robotic animals, or construction kits) to extend the range of behaviors of these objects. (Cf. [15]) In our own lab, we have explored designs of this sort as well [9, 21, 22]; but for the purposes of this paper, our focus will instead be on a different sort of "physical/virtual integration", in which desktop computer systems are combined with a range of output devices (both new and old), enabling users to create and custom-design educational artifacts of various sorts. In effect, then, this paper is about the general idea of "printing"—but our goal is to invest that undeservedly mundane word with a good deal more variety and romance. Following the inspiring example of Vannevar Bush's influential 1945 paper "As We May Think", in which technology was imagined as a means of augmenting the human intellect [14], we argue

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that technology can likewise be a means of augmenting the traditional, solitary, manual powers of the craftsperson, student builder, hobbyist, and designer. Rather than a stand-alone (or even merely Web-connected) symbol processor, we argue that a truly powerful “educational computer” can in addition be viewed as the central device within a home workshop or school shop class. This in turn implies that computers can act as a long overdue means of bridging the hitherto disparate traditions of “vocational” and “theoretical” education, with their respective emphases on building and working with abstract symbols.

The remainder of this paper is devoted to unpacking the argument of the previous paragraph by use of several projects currently underway in our lab. Although these projects are at various stages of maturity (and, individually, none of them is very far advanced), they collectively illuminate a variety of approaches to the process of “printing”. By making use of both established and novel output devices and materials, these projects indicate possibilities for rethinking and reinvigorating traditional children’s craft activities, or for designing new ones.

The following section of this paper briefly describes in turn each of our sample projects—highlighting, along the way, the manner in which each project touches upon particular issues related to the notions of “output” and “printing”. The third section summarizes and extends these examples by presenting a series of design heuristics—ways in which educational designers can systematically approach the burgeoning landscape of possibilities afforded by new output devices and materials. We conclude with a brief description of related work, as well as ongoing and potential future directions for research.

## CRAFT APPLICATIONS FOR CHILDREN: A SMORGASBORD OF VIEWS ON THE OUTPUT DEVICE

In this section, we present descriptions of those various recent projects in our lab relevant to the broader redefinition of “output” for children’s crafts. Necessarily, each of these descriptions will be rather telegraphic; here, we only intend to present sufficient detail to convey the overall purpose and design of each system.

### Pop-up Workshop: Paper Engineering for the “Traditional” Printer

As many teachers and parents are aware, building pop-up books and cards can be a compelling creative activity for children. Pop-up forms manage to combine, within a single artifact, artistic and creative invention, spatial and mechanical motions of paper, and (often humorous) writing. Perhaps reflecting this positive evaluation, several how-to books for children on the subject already exist (e.g., [1], [7]]). Nonetheless, pop-up making can also (as with many children’s papercrafts) be a source of frustration: it is often difficult to create a particular desired pattern of cuts and folds on the flat page that will correspond to a desired movement in three dimensions; and it can be a tedious job to experiment with a variety of two-dimensional patterns, since each experiment must be precisely enacted with a separate sheet of paper. As a result, it is likely that few children achieve anything resembling expertise in this form; and for the vast majority of children, many of the most interesting issues in design (e.g., recursive folding patterns) remain unexplored.

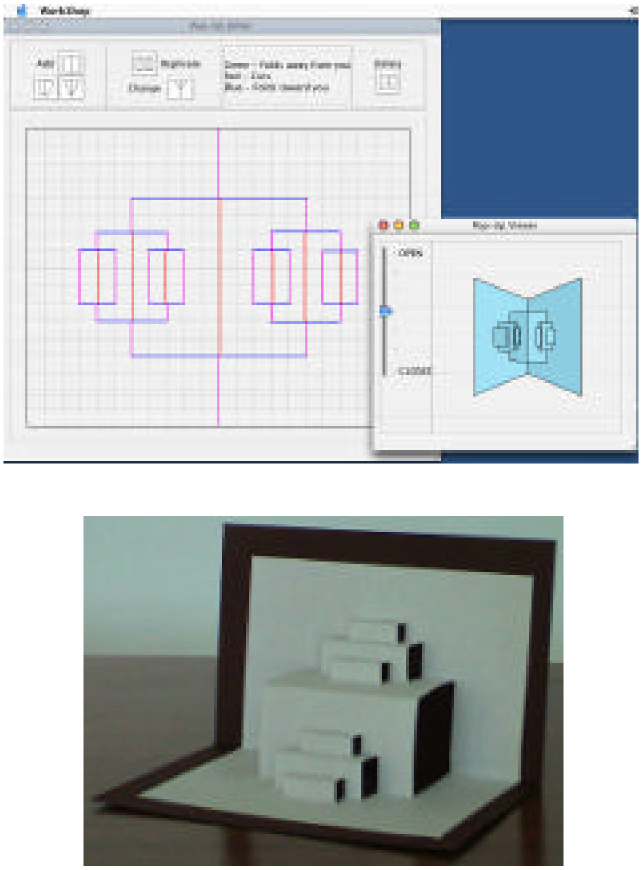

Figure 1. At top: a screenshot of Pop-up Workshop in the course of a typical scenario. The larger window shows the template of cut and fold lines; the smaller window at bottom right depicts an interactive rendering of the eventual popup form which may be “opened” and “closed” on the screen to varying degrees. At bottom: the popup construction made according to the design shown above.

The *Pop-up Workshop* system, currently in development, is an application through which children will be able to design and view popup forms on the computer screen, and then print out templates which can be cut and folded into functional popup cards and books. It is worth mentioning at the outset that this application is not, emphatically, intended to supplant or replace the activity of physical construction; after all, there is little excitement to a purely graphical, “virtual” popup form on the computer screen. The purpose of Pop-up Workshop, rather, is to permit children to explore a variety of designs (many of which would likely be unimagined, or prohibitively complex, in the absence of a design tool); in the process, students can become more proficient “paper engineers” and develop a far more powerful repertoire of design in this form.

Figure 1 (top) shows the current version of Pop-up Workshop in the course of a typical scenario. Here, the user has created a template of cuts and folds for a recursive pattern of “90-degree parallel folds” (i.e., pop-up folds that are best displayed at a 90-degree opening of the page). The larger window at the left of the screen shows the pattern of folds and cuts, color-coded to show which lines represent cuts, “mountain” folds (toward the user) or “valley” folds (away from the user). The smaller window at the bottom right of the screen shows a rendering of how this pattern will appear when the pop-up form is constructed in paper; the slider in this smaller window permits the user to view the constructed form at various degrees of opening. Once the user has printed out and constructed the actual paper form, it appears as in the photograph at the bottom of Figure 1.

Pop-up Workshop (like our earlier program, HyperGami, for constructing polyhedral models and sculptures [10]) requires only a standard color printer of its user. Nonetheless, the program—by virtue of its design and functionality—suggests ways in which other types of output devices might be employed in addition to, or in combination with, the color printer; we will return to this issue in the final sections of this paper.

### Spectre: Building and Visualizing Three-Dimensional Objects via Transparency

The second project to be described in this section is based on a simple, homemade device described over fifty years ago, in a beautiful book of mathematical crafts entitled “Mathematical Models” by Cundy and Rollett [5]. The device, as described in their book, is intended for use by mathematics teachers to depict three-dimensional forms. Figure 2 (taken from the original source) shows a diagram of the viewing device: a series of parallel shelves on which glass panes can be placed in layered fashion. Each of the glass panes (Cundy and Rollett suggest the use of lantern-slide plates) depicts a cross-section of a particular solid, drawn with colored pencil. When the entire sequence of glass panes is viewed, a three-dimensional rendering emerges.

While such a device is ingenious, making use of the device as described in the early 1950’s would represent a considerable investment of time for any teacher or student. Obtaining a sufficient quantity of glass panes would be expensive; and the effort involved in hand-drawing precise cross-sections would be prohibitive. (And of course we needn’t dwell on the potential for accidents involving the cracking or shattering of glass!) Presumably as a result of these drawbacks, the Cundy and Rollett device seems to have had little influence on classroom practice, despite its potential.

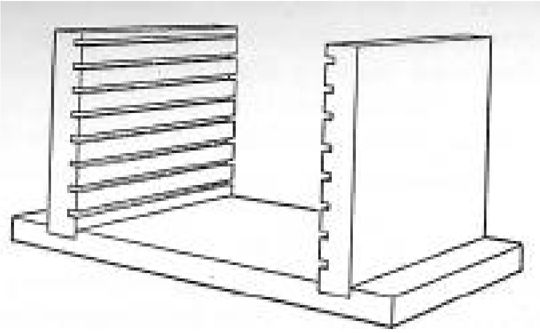

Figure 2. The homemade device for viewing three-dimensional solids (from [Cundy and Rollett, 1951]). The construction is simply a series of parallel shelves into which layers of glass (or, in the case of our Spectre system, transparency) may be inserted.

We have created a software system, *Spectre* [3], that makes use of this fifty-year-old idea by allowing users to create three-dimensional forms on the computer screen, and to print out a sequence of cross-sections of those forms on plastic transparency sheets. These sheets (which replace the glass panes in the original description) may then be layered into the Cundy and Rollett device; the result is a truly striking three-dimensional view of the desired solid shapes. Figure 3 shows a screenshot of the application (at top): here, the user has created several standard solid shapes (a cone, cylinder, and sphere), and the program creates a sequence of cross-sections of the scene for printing out (one of these is shown in the larger window at the left of the screenshot). At the bottom of Figure 3, we see the resulting display once the transparency cross-sections have been printed out and assembled. The name “Spectre” for this system reflects the impression created by the resulting display: the effect is of a set of ethereal shapes, hovering in midair.

As with Pop-up Workshop, the only output device assumed by the Spectre system is a color printer; but there are a couple of additional points worth noting. First, Spectre makes use of plastic transparency instead of paper; in this sense, the program is employing a somewhat less traditional output material. More interestingly, in order to use Spectre, the user must create an additional output artifact (the Cundy and Rollett viewing device), to be employed in tandem with the already-existing output device (the printer). In this sense, the Spectre system suggests a style of work in which the user, through homespun materials, is able to supplement the existing landscape of commercial output devices. Again, this point will be discussed in the final sections of this paper.

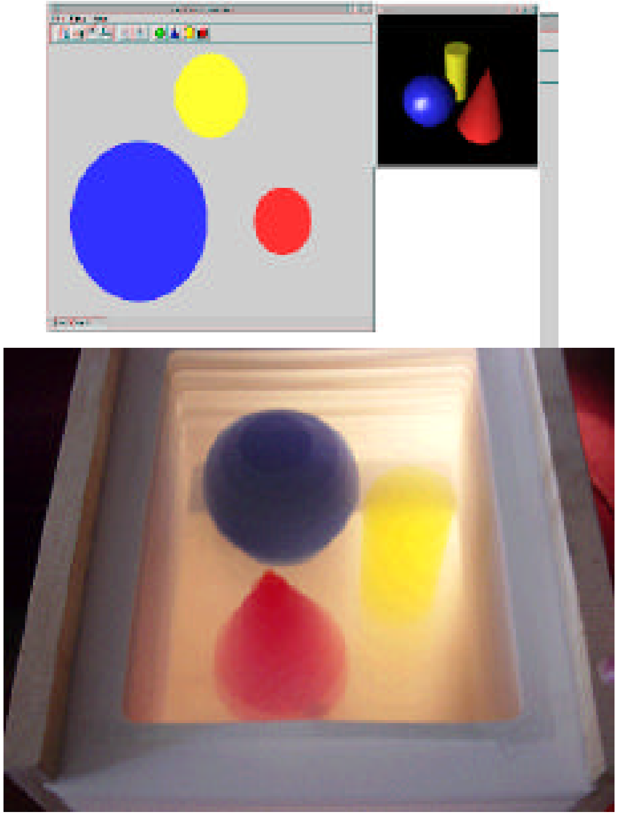

Figure 3. At top: a screenshot of the Spectre system, showing a three-dimensional rendering of several simple solid shapes, and (in the larger window) one of the graphical cross-sections produced by the program. At bottom: once the cross-sections are printed out in transparency and inserted into the Figure 2 viewing device, the result is a surprisingly effective rendering of the solids in three-dimensional space.

### Sliceform Builder: Creating Wooden Models of Mathematical Surfaces

The third application to be described here, *Sliceform Builder*, is a system (at a very early stage of development) for the creation of mathematical surface models in wood. The basic idea behind this type of construction can be found in [18]: briefly, in order to create a model of a function from $x$ and $y$ to $z$, one creates two series of slotted planar forms—one series parallel to the x-axis, and one parallel to the y-axis. The two series of planar "slices" fit into one another through their respective slots. Figure 4 shows (at top) a sample pair of wooden Sliceform Builder pieces for constructing a paraboloid; the bottom of the figure shows the fully-constructed paraboloid surface. The overall purpose of Sliceform Builder, then, is to permit students to specify an appropriate surface function; the program produces sequences of slotted pieces that can be assembled into models such as the one shown in Figure 4.

Sliceform Builder is thus (like the earlier two applications) capitalizing on a traditional idea for creating physical artifacts for education; the notion of "sliceform models" is hardly a new one. But the program permits students to experiment with a wide variety of complex surface models and to produce those models without painstaking (and usually error-prone) calculation. Again, the program is not intended to supplant the model-building activity: there is little excitement to a purely graphic representation of a sliceform surface model. In fact, the physical construction, once assembled, is not only an attractive object for display: it also provides a tactile experience of the plotted function (one can "feel" the paraboloid surface on the construction in Figure 4).

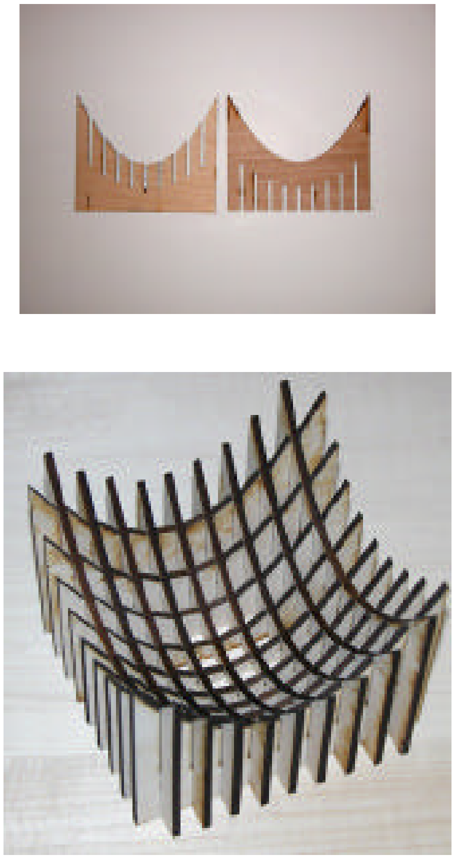

Figure 4. At top: two individual sliceform pieces for a paraboloid construction. One piece (corresponding to the x-dimension) has slots at the top; the other (a y-dimension piece) has slots at the bottom. At bottom, when the two sequences of pieces are slotted together, we produce a model of the paraboloid surface in wood.

Although the program may be used to produce paper models, we have employed Sliceform Builder to output its forms to a laser cutter, to produce pieces in wood, as in Figure 4. This is a principled choice: wood is a far better medium for these models than paper (paper sliceform models tend to collapse and bend easily, and they are much harder to assemble). The laser cutter itself is shown in Figure 5: it is an output device similar in design to a line-plotter, except that instead of a moving pen over a piece of paper, the laser cutter employs a moving laser to cut forms out of planar slices of wood, foam core, and certain types of plastic. The laser cutter is thus an output device that supplements standard printers by permitting users to “print out” in a variety of new materials; and often (as in the case of our sliceform constructions), these alternative materials are superior to paper for particular purposes. The next application to be described, MachineShop, also makes use of “printing in wood”, and we will return to the question of alternative output devices in the following sections.

Figure 5. A laser cutter in operation. Here, the table is moving underneath a (stationary) laser to produce wooden cutout pieces, much like those shown in Figure 4.

### MachineShop: Building Mechanical Components in Wood

*MachineShop* [2] is an application-in-progress that (like Sliceform Builder) makes use of a laser cutter to produce customized forms in wood; here, the forms are mechanical elements (such as gears and cams) for the production of homemade wooden automata. Figure 6 shows a set of representative mechanical pieces (at top), and (at bottom) a “sea monster” automaton that employs several custom-designed eccentric cams (and associated ring followers) produced by the system.

MachineShop consists of a number of modules for the creation of mechanical elements. Figure 7 depicts one recent addition to the program: a “mechanism explorer” that permits the user to select potentially interesting mechanisms according to the type of qualitative input and output motions desired. In the scenario shown in Figure 7, for instance, the user has selected “circular” motions for both input and output movement (with no additional motion options such as changing direction or changing the plane of movement): the system presents a couple of possible mechanisms with the desired characteristics, and the user examines one of these (a series of spur gears). The explorer also can present a video clip of the mechanism in operation (toward the upper left of the window).

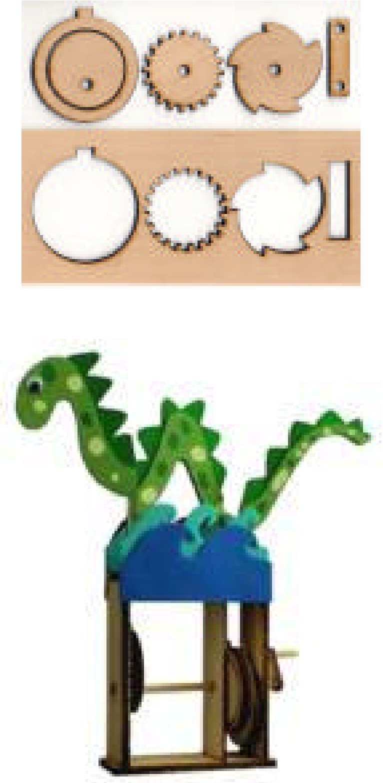

Figure 6. (top) A set of mechanical elements printed out in wood. The element at the left of this set—an eccentric cam with a ring follower—is used several times over in the construction of the homemade sea monster automaton at the bottom of the figure.

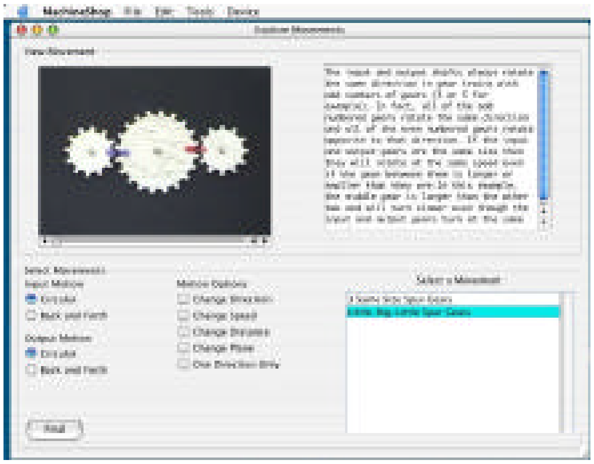

Figure 7. MachineShop’s mechanism explorer module. Here, the user is examining the circular-to-circular motion of a series of spur gears.

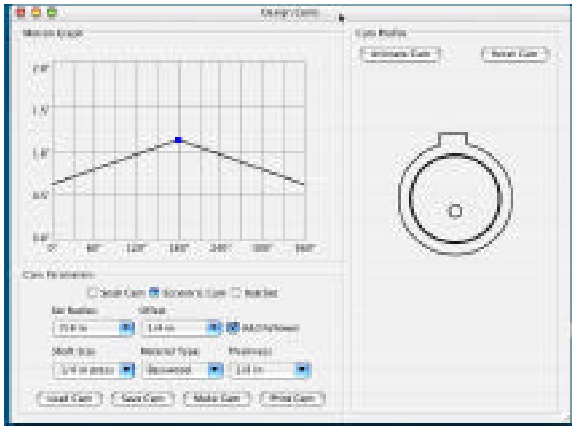

Figure 8. MachineShop’s editor for the eccentric cam. The user selects a variety of parameters for the cam and “prints out” the component in wood. The graph at upper left shows the movement of the ring follower (up and down) over one cycle of the cam.

Once the MachineShop user has settled upon a desired mechanism to construct, she can bring up an appropriate editor for that type of mechanism. Figure 8 depicts one of MachineShop’s operational editors—this one for an eccentric cam of the type used in the automaton of Figure 6. The user selects a variety of parameters to customize the cam, and can observe a graph showing the time-portrait of the cam at the upper left of the window (in Figure 8, this graph shows the up-and-down movement of the cam follower over one cycle). Once the desired movement has been achieved, the user can “print out” the cam in wood to produce a component like the one shown toward the left in the upper photo of Figure 6.

## AVENUES FOR INNOVATION: SOME PLAUSIBLE DESIGN HEURISTICS FOR CHILDREN”S CRAFT APPLICATIONS

The previous section described a variety of current projects focusing on the design and physical creation (via “printing”) of educational artifacts. In this section, we use these various examples as a springboard for discussing the ways in which educational designers might explore many other types of “computationally-enhanced craft” projects that make innovative use of output devices and materials. What follows, then, is a set of useful heuristics—not so much rules as avenues of thought—for those designers interested in pursuing these themes.

### Heuristic 1: Exploring the space of existing (though not always accessible) output devices

The examples described in Section 2 focused on a relatively small corner of the existing landscape of output devices, many of which—although conceived and advertised as industrial devices—have interesting potential for school and home-workshop applications. Examples of these alternative output devices include three-dimensional printers (for printing out forms in plastic), milling machines (which can be used to cut or engrave customized forms in metal and plastic), knife cutters (similar to the laser cutter in design, but using a knife to directly cut paper or fabric), water cutters (which use an extremely thin jet of water under high pressure to cut metal), specialized “thermal printers” (that use specialty papers for producing raised print and graphics, often used for printing in Braille), and many others. Conceivably, these devices could be used by students (with appropriate design and accompanying software). Just to suggest one example: the Pop-up Workshop system might eventually make use of printers that cut paper (to produce the appropriate cuts in popup templates without the use of a handheld knife or sharp scissors).

Often, when such possibilities are raised, there is an objection that these devices are too expensive, hazardous, or difficult for use by students or amateurs. Our own belief is that these objections do, for the time being, carry some force—but only because these devices are currently conceived as industrial machines, out of the reach of “ordinary” users (and certainly out of the reach of children!), much as computers themselves were viewed in the 1960’s and 1970’s. One important theme of research, then, over the coming decades should be to devise smaller-scaled, simpler, less expensive, and safer versions of these devices—in effect, to create pathbreaking fabrication and craft devices in the spirit of the first home computers of the late 1970’s and early 1980’s.

### Heuristic 2: Exploring the space of output devices that could exist, but don’t

The previous paragraphs focused on experimenting with commercially available (but rarely educationally-oriented) output devices. But the example of the Spectre system suggests still another approach to designing children’s craft applications, which is to work toward building new sorts of homemade or experimental output devices and accessories. In the case of the Spectre system, the “homemade hardware” is a relatively simple collection of shelves (our version of the viewing device was, in fact, rather carefully built out of wood); but there are many other output devices that could, conceivably, be created, and that could have especially powerful applicability to children’s crafts. One example along these lines would be a device to print out designs on thin strips of paper tape (many interesting mathematical solids can be constructed from weaving together such strips [19]); another possibility would be a device for printing out custom-colored lengths of yarn or string (this could be used for the creation of string sculptures and woven mathematical designs such as temari balls [20]).

A much longer and more detailed argument along these lines may be found in [9]; but essentially, the point to be made is that relatively few output devices geared toward children’s activities exist at the moment, and that creating such devices could easily comprise an interesting research agenda in its own right.

### Heuristic 3: Exploring the space of children's crafts and artifacts

Several projects in Section 2 are based upon venerable (though often, unfortunately neglected) educational craft activities: popup building, sliceform assembly, and the building of mechanical toys. In each of these cases, a well-designed software application can be used not only to expand the range of what children can construct, but also to expand and refine the vocabulary and notation around the construction activity itself. A student using MachineShop's cam editor, for example, may find herself specifying parameters of the cam's design (such as the placement and dimensions of cam features) that would otherwise remain implicit or unexpressed; a student using the Pop-up Workshop system may reflect upon notions such as recursive placement of popup elements that would otherwise be too difficult to envision or attempt.

There are vast numbers of still-unexplored craft activities for children that could form the basis of interesting experiments in software and output-device design. The possibilities include: mosaic design, bead-pattern design, sand painting, and the like. Perhaps even more interesting are the possibilities for exploring activities surrounding popular children's artifacts that could be custom-designed and fabricated with the appropriate software and hardware. Conceivably, children could create and "print" their own tops, kaleidoscopes, construction kit pieces, jigsaw puzzles (in both 2- and 3D), mathematical puzzles, polyhedral dice, kites, balancing toys, customized optical illusions, and many other objects. Thus, by enriching the space of children's constructions with software and hardware designed for that purpose, it may be possible to reconceive the landscape of children's artifacts less as a collection of commercial items (such as kits and toys), and more as a collection of empowering tools and techniques with which children can create their own personalized, high-quality artifacts.

### Heuristic 4: Exploring the space of new materials

One of the more provocative ways in which to explore the potential space of children's craft activities is to look to technological advances not in software or hardware, but rather in materials science—that is, to look to the burgeoning variety of novel stuff available for experimentation and construction. The "thermal printers" mentioned earlier in this section, for instance, make use of specialized papers which can swell or expand (at certain designated areas) with the application of heat; conventional printers can make use of transfer papers for producing designs on fabric (these papers are generally used to produce customized T-shirts, but other craft activities are possible). Slightly more futuristic output materials include conductive inks (that might allow users to "print out" working circuits onto specialized substrates) or "programmable paper" (flexible materials—essentially flexible "screens"—that can be programmed to display animated patterns). In effect, these new materials can expand the range of stuff with which children can build beyond the already-established examples of paper, wood, string, and plastic.

### Heuristic 5: Social and Environmental Factors

As mentioned earlier, one of the potential barriers to the sort of research described here involves issues such as safety, "child-friendly" design of output devices, and simplicity of operation of tools (both hardware and software). An important line of research, then, is to find innovative ways of encouraging craft and fabrication activities that are (on the one hand) safe, but (on the other) not so safe and carefully prescribed as to be bland and predictable. Consider, for example, the laser cutter as an output device: although increasingly affordable and undeniably versatile, laser cutters present certain hazards. Materials may sometimes catch fire, and certain (inappropriate) plastics, if used in the laser cutter, may give off noxious fumes. To make "classroom-friendly" laser cutters, then, will be an engineering challenge—though, in our view, a challenge that can likely be met. (For example, a laser cutter manufacturer might market their own line of wood or plastic sheets for exclusive use in the device, thus discouraging the use of inappropriate or hazardous materials.)

Some of the innovations regarding children's crafts might be matters of designing supportive environments or social infrastructure. Three-dimensional printers, for instance, might be (for the near-term future) too expensive to be considered as devices for the home, or for all but a few schools. Nonetheless, one might imagine neighborhood clubs or workshops in which such large-scale output devices could be collectively used and maintained; or perhaps such devices could be associated with commercial copy centers, where users could go to print out or fabricate individual objects. Much as in the realm of home computing—an innovation whose growth in the 1980's was associated with clubs, local interest groups, informal classes, popular magazines, and so forth—the realm of home and classroom fabrication and crafting may well need to accompany technical innovation with a cultural sea change.

## RELATED, CONTINUING, AND POTENTIAL FUTURE RESEARCH

There are a number of research efforts that—in a general sense—involve the integration of physical and computational media. The strongest influence on the work described here originates in the research of M. Resnick and his colleagues at the MIT Media Lab—particularly in the development of the programmable Lego brick [16] and the innovative collection of "digital manipulatives"[17]. Likewise, M. Gross and his group at the University of Washington have developed creative blends of physical objects (such as building blocks) and powerful applications (see, for instance, [4]). For us, what distinguishes these efforts is the emphasis not on blending computation and physical media per se, but particularly the element of integrating computational media into both traditional and nontraditional design and construction activities. Philosophically, this emphasis on children's activities as a central aspect of educational design (rather than, say, tutoring systems or other means of delivering educational content) is particularly well expressed by diSessa [6] (although the system development described in that book follows different lines than the systems described here).

The systems described here are all in the process of continuing development; in particular MachineShop, Pop-up Workshop, and Sliceform Builder will be developed well beyond their current levels of implementation as described here. In the near to middle-term future, our more mature systems will be evaluated (both informally and with formal studies) with users, and will be made available over the World Wide Web. As these earlier systems mature, we also hope to develop a variety of additional prototypes illustrating some of the themes described earlier—e.g., exploring new commercial and home-built output devices, looking to means of creating and "printing out" children's artifacts, and experimenting with novel and powerful materials for design.

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