Printing Reconsidered: Exploring New Directions for Output Devices in Educational Technology

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Introduction: Computation and Real-World Materials
In debates over the role of technology in education, computers have traditionally been cast as the cause of a malign “virtualization” of children’s experience—a means by which children lose, to an ever greater extent, the pleasure and feel of work with real materials. One widely-cited cover story in *U.S. News and World Report* sounded this theme eloquently:

> It is the real-life lessons—the climbing over and scooting under, putting one cup inside another, and chasing Cheerios around the kitchen floor—that teach a child how the world and his body work. Pushing a computer key to make an animated monkey dance does not have the same effect. “Two-dimension play is not as good as three-dimension play,” says Kathy Hirsh-Pasek, director of the Infant Language Lab at Temple University in Philadelphia. ([6], p. 51)

A similar note is sounded by Healy in her book *Failure to Connect* [5]:

> The greater danger… is not that children will occasionally enjoy an interesting software program, but that in spending too much time on two-dimensional computers, the child will adopt an iconic mode of reasoning that bypasses real-world foundations. (p. 222)

Although Healy’s focus in these remarks is on younger children, she also adds:

> Even for older children, a computer simulation of a chemistry experiment is decontextualized: no smells, no broken test tubes, nothing goes wrong, except in a preprogrammed way.(p. 221)

The concerns voiced by these authors are (in our view) important ones, and there is more than a little truth to the traditional stereotype of computers as “de-physicalizing” devices in children’s lives. Still, this paper argues that—whatever the merits of the critics’ arguments—the traditional stereotype promises to be far less true in the coming decades of educational computing. A number of developments point in this direction—importantly including the advent of small computers (such as the programmable Lego brick) suitable for embedding within children’s craft constructions.[7, 8, 9] This paper focuses on yet another technological development that portends an increasing rapprochement between the physical and computational poles of the educational experience: namely, the advent of powerful, and increasingly affordable, output devices. Broadly put: the ability to “print out” in materials such as wood, foam core, and plastic suggests that computers, rather than being representatives of an over-virtualized educational culture, may instead become the intellectual sparkplugs of a revived, enhanced, and vastly more expressive “shop” tradition for children. Perhaps just
as important, such devices can help us to rethink the landscape of artifacts in science and mathematics education—to see these artifacts less as objects of consumption, and more as the potential fruits of children’s construction.

Consider, for example, the homemade mechanical sculpture shown in Figure 1: a wooden automaton of a winged buffalo turned by a crank. When the crank is turned, the eccentric cam toward the base of the sculpture causes the buffalo body to move up and down; and the two wings attached to the sides of the animal, attached to two straight wires, are pulled downward and pushed upward in synchrony with the buffalo’s movements.

Although not terribly complex from a purely mechanical standpoint, such a construction would be difficult both to design and create with the sorts of tools typically available to younger students. Most likely, if children have any experience with such automata at all, it is as consumers: a device like this might be purchased whole, or as a relatively non-creative kit of pieces to be glued or snapped together. As it happens, though, the individual pieces of this automaton were printed out on a low-power laser cutter (with the exception of the cylindrical dowels; the wings, which are done in transparency; and the metal wires attached to the wings). What this suggests is that mechanical automata—and indeed, many other intellectually rich artifacts for children—can be re-interpreted as the endpoints of constructive and creative activities. Rather than purchase pre-built devices, students—empowered by a new generation of “printer”—can encounter mechanical engineering (or other fields) in a much more personalized and expressive way, becoming designers of their own scientific and mathematical objects. And within such activities, computers—rather than being a means of distancing children from real-world materials—can be the instruments that enable still-more-powerful (intellectually and emotionally) encounters with those materials.

In the remainder of this paper, we use a system-under-development as a foundation for discussing the role of output devices in educational technology. MachineShop is a software application for the design of mechanical automata realized in materials like basswood or balsa. As such, it is a system somewhat in the spirit of our earlier HyperGami program (in which children design customized three-dimensional polyhedral shapes on the computer and then print out flattened “folding nets” for those shapes on a color printer [3]): both MachineShop and HyperGami may be viewed as design applications for physical materials. However, whereas HyperGami made use of a fairly well-established output device (the printer) as the source of physical construction, MachineShop is intended to work with a laser cutter. Although the program is still in a
relatively early stage of development, our experiences with MachineShop to date have highlighted a number of interesting and (to us, at any rate) unexpected issues in adding “printers for wood” into the landscape of technological artifacts for children.

The following section presents a brief description of the MachineShop system in its current state. Following this, and using MachineShop as an intellectual springboard, we discuss what we believe are important issues in rethinking the role of output devices in children’s technology. In the fourth and final section, we discuss related work and a variety of directions for future research and development.

**Figure 2a**(left): A mechanism browser screen. **2b** (right): A component (cam) browser screen. Both these modules are under development in MachineShop.

**MachineShop: A Children’s Design Tool for Mechanical Automata**

The basic intent behind MachineShop is that it should ultimately permit students (and adult hobbyists) to design and create an infinite variety of mechanical toys in wood. As such, it can be seen as an educational system introducing users, through creative craftwork, to fundamental ideas in mechanical engineering and mechanical physics. In its current state, several of the elements of the program are operational, while others exist only in rudimentary or “mock-up” form, and still others have yet to be tackled at all; here we will attempt to describe our overall vision for the program, while simultaneously noting which elements are in various states of progress.

A user might begin employing MachineShop by invoking a “mechanism browser” such as the one suggested by the mockup screen in Figure 2a, at left. Here, a variety of types of mechanical movement are shown in three-dimensional form. In the figure, for example, the mechanism at right is an eccentric cam (with a ring follower) much like the one shown in the base of the flying buffalo device of Figure 1. By selecting a desired type of mechanism—such as the eccentric cam—the user should bring up a browser for particular types of mechanical components—such as cams—relevant to constructing the mechanism. Figure 2b at right shows a (likewise still incomplete) cam browser through which a variety of cam component designs may be explored.

Once the user chooses a basic component, she should then be able to select the “Load” button to invoke a design tool for the particular sort of component in question. Figure 4 shows the cam component editor (which is in a relatively mature state of completion). In
the figure, the user is designing an eccentric cam (shown with its ring follower around it). The outline of the cam is shown toward the bottom right of the figure; toward the upper left is a graph that shows the vertical movement of the cam follower as a function of time when the cam is turned at a steady rate. Key parameters of the cam may be altered by selecting among the choices shown in the drop-down menus toward the left labeled “base radius” and “offset”. A similar component editor—with more powerful customization features—is also available for so-called “snail cams” (see the description in [1]), and still other component editors (including one for gears of various designs) are in the works. Once the user has constructed a particular form of cam, she may add that to the component browser of Figure 2b by selecting the “Save Cam” button toward the bottom left.

![Figure 3](image.png)

Figure 3. A (largely operational) component editor for an eccentric cam. A similar (and also operational) editor with additional features exists for so-called “snail cams” as well. The device being designed is shown in sketch form at right; at upper left, a time-vs.-position graph of the cam follower; at lower left, a variety of customization controls for designing and then “printing” the cam in wood.

For the purposes of this paper, one of the most interesting aspects of Figure 3 is represented by the drop-down menu selectors labeled “Material Type” and “Thickness” toward the bottom left of the screen. By selecting a particular type and thickness of wood, and then selecting the “Make Cam” button, the user tells MachineShop to produce a file (composed of HPGL commands) that can be sent to a laser cutter for fabrication. Figure 4a shows our laser cutter in the process of creating a piece; essentially, this output device is designed along the lines of a line plotter, in which a mobile laser moves in a programmed way over a stationary slab of wood (or some other appropriate material), cutting an outline as it goes. (As it happens, in our laser cutter, the laser is stationary and the table holding the material is moved according to program commands.) Figure 4b shows the result of several such operations: a set of wooden pieces fabricated by the device (including, at left, the eccentric cam of Figure 3), along with the piece of wood from which they have been cut.
Output Devices in the Learning Sciences

Having introduced MachineShop in the previous section, our purpose in this section is to step back from the program and employ it as a source of issues for discussion. MachineShop is just one instance of an educational application; and it is a highly domain-specific (and still incomplete) application at that. Nonetheless, we believe that the system raises issues that are part of a larger, proactive conversation in educational technology—a conversation that goes well beyond the particular program shown here, or the particular domains of mechanical design and engineering.

The Purposes Served by Output Devices: Decoration, Shaping, and Display. One way of reflecting on the MachineShop example is to ask what purpose is served by an output device such as the laser cutter. We often find ourselves describing the laser cutter as a “printer of wood”, via a kind of rhetorical shorthand. But in MachineShop (and in many industrial applications), the laser cutter does not function in the way that a paper printer does: in particular, the laser cutter acts for us as a shaper, rather than decorator of materials. These two functions—shaping and decorating—reflect two of the major functions of output devices in general. A desktop paper printer may be seen as a device that decorates the exterior of a surface; while there are other output devices (typically found in industrial contexts) that act as shapers for materials such as paper, plastic, and textile. Going just one step further: a third function, beyond shaping and decoration, may also be added to our list of output-device purposes. If we consider screens as output devices, then such devices may also be used as means for rapid, dynamic information display.

The divisions between these three output functions—decoration, shaping, and display—are not always clear-cut, even within a single device. For example, a laser cutter may act both as a material shaper and as a decorator (closer in spirit to a paper printer): by setting the laser at low power, it can be used to engrave surfaces as well as cut through them. Similarly, at least some line plotters (a “decorative” device) have been equipped with knives instead of pens to cut paper. Still, thinking in terms of these functions appears to be a salutary exercise in imagining possible craft activities and output devices.
One might, for instance, imagine an educational output device whose sole purpose is to decorate certain representative classes of geometric surfaces (such as cylinders or spheres), or to display (or project) information on such surfaces. Or one might try to design material-shaping devices for other educationally useful materials (such as wax). [Cf. [2]] We will return to these issues in the final section of this paper.

Output Device Drivers and “Materials Education.” In the previous section, we noted that MachineShop employs drop-down menus that the user can employ to customize output for a particular material. One straightforward way that we could describe this functionality is to say that MachineShop has incorporated the basic elements of an output device driver: i.e., much as a word-processor user might specify that he wishes to print a document on glossy paper, a MachineShop user might likewise specify that he wishes to print a cam on quarter-inch basswood. While this analogy is not unreasonable, those researchers interested in the issues raised at the outset of this paper—the relationship of children to real-world materials—might wish to push on the analogy just a bit. After all, the purpose of a traditional output device driver is to shield the user as much as possible from any need to understand the workings of the printer, or the fine details that distinguish one type of material from another. In other words, a traditional output device driver has no *educational* mission: a standard printer driver interface assumes that users are uninterested in (e.g.) different types or grades of paper, or in the design of the printer itself.

In contrast, the advent of new output devices for education might suggest a different outlook. Arguably, the community of system designers should regard the “driver” program as integrated into a larger introduction to the behavior and culture of materials; and just as craftspeople often develop a closer understanding of their tools, so by the same token a “driver” should be regarded as a budding craftsperson’s program—an introduction to the design and engineering behind the output device. In the case of the MachineShop system, there is very little of this educational dimension to the “driver” functions of the current program; but including a “materials-education” module is one potential extension to the system.

What Makes for a Good Educational Output Device? Perhaps the central question raised by the burgeoning variety of actual (and potential) output devices in education is: what role do, or can, these devices play in learning? This is a topic for a much longer discussion, but our general thematic response to this question is to begin by exploring the landscape (traditional and otherwise) of contentful physical materials for children: things like tops, kaleidoscopes, music boxes, yo-yos, mathematical puzzles and manipulatives, scientific instruments, and so forth. We might then begin to reinterpret these objects as the foci of potential craft activities—and, by extension, as the products of output devices. In general, we would argue (though this is an empirical question) that the design of such objects is a richer experience for children, intellectually and affectively, than their purchase. And by structuring our thinking around the types of meaningful objects that children often have, we can reimagine similar classes of objects for children to build.
Related, Ongoing, and Future Work
The design of MachineShop reflects a larger interest in blending physical materials and computational media for children. There are numerous examples along these lines, though our primary influences are in the work of Resnick and his colleagues at the MIT Media Lab [8, 9], e.g., in the development of computationally-enhanced “digital manipulatives”; in particular, the emphasis of this group is on devising design activities for children rather than simply (as in the case of some “smart toys” [7]) embedding complex behavior inside physical artifacts. A particularly provocative discussion of future output devices, and their potential role in education, can also be found in Gershenfeld [4], who looks toward the future of a “Personal Fabricator” device.

Our near-term goal is to continue to develop the MachineShop program (e.g., adding a working mechanism browser; adding more working component editors; and adding a module through which simple components may be joined together into mechanisms and simulated before printing), and to conduct a variety of assessment activities with children using the system. In the longer term, though, we prefer to see MachineShop as one step in a much larger (and we hope widespread) research agenda of integrating powerful output devices into children’s learning and experience, and studying the cognitive consequences of that integration. Certainly, there is much to be done: many other output devices—3D printers, holographic printers, “digital paper”, and so forth—are either commercially available or on the near-term horizon, while the discussion of the previous section (and [2]) suggests that still other fascinating, and as-yet-unimagined, educational output devices are waiting to be designed.

Acknowledgments. Thanks to Eric Scharff for contributing to this work, and to Carol Strohecker for inspiring and encouraging it. This work was supported by NSF ROLE grant #0106976, and by a gift from Mitsubishi Electric Research Laboratories (MERL) in Cambridge, MA.

References.