Educational Fabrication, In and Out of the Classroom
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Abstract: A technological revolution in children's construction is now poised to occur—a revolution founded upon the advent of accessible fabrication and printing devices. Increasingly, children (and schools) have access to laser cutters, 3D printers, paper cutters, computer-controlled sewing machines, and a variety of other powerful output devices. In concert with the process of technological evolution, however, a cultural evolution must likewise occur in re-conceiving fabrication for children. Much as computers themselves needed to be understood as something other than industrial devices, so do fabrication tools need to be imagined as part of children's worlds. This paper discusses several important dimensions of the cultural evolution that needs to take place—namely, the dimensions of materials, subject matter, and physical settings—in altering our collective view of fabrication and construction activities for children.

Introduction: A Revolution-in-Progress

It was not so long ago—perhaps a decade or so—when the notions of "children's computation" and "children's construction" were almost entirely distinct. In that distant era, computers were seen as tools for a kind of work that might (depending on context) be called "abstract", "symbolic", "information-based", and so forth. By implication, children's computational activities—whether playing games, composing multimedia reports, searching the Web, running simulations, or writing programs—were resolutely separate from their physical activities with tangible materials. Children might work on the screen, or they might work with their hands; but not both.

This state of affairs has changed. While the intangible, purely screen-based aspect of computation remains central—and while wonderful things continue to be done in this vein—it is increasingly clear that computational and physical activities for children can be productively integrated. There are numerous pathways for this integration, but for the purposes of this discussion we can focus on the advent of powerful, accessible computer-controlled output and fabrication devices. Computers can be used to "print out" high-resolution, complex physical objects in materials such as paper, textile, wood, metal, and plastic; and these printed-out objects can now be designed, customized, and used even by elementary school-aged children. (For an early but still provocative discussion of this technology, see [4].) What this means, in effect, is that computers—along with handsaws, hammers, drills, screwdrivers, paintbrushes, scissors, and sewing kits—are now part of the standard toolset of children's construction. Computers are now at the heart of a new incarnation of "shop".

To a large extent, though, this perception has yet to sink in—whether among schools, manufacturers, or (for the time being) among children themselves. Indeed, in some ways, the parallels between the current revolution and the earlier history of home computing are striking. It is easy to forget how unlikely the very idea of "children's computing" seemed for decades after the first invention of the computer. Throughout the 1950s and 1960s, computers were large-scale, expensive devices; and they were (not implausibly, given their expense) seen as industrial devices, to be used only by highly trained (and by assumption, adult) professionals.

A delightful example of this once-upon-a-time cultural attitude toward computers—and their likely users—can be found in Woody Allen's 1969 film Take the Money and Run. In that movie, a career bank robber (named Virgil Starkwell, and played by Allen himself) tries to lie his way through a job interview:

INTERVIEWER: Have you any experience in running a high-speed digital electronic computer?
VIRGIL: Yes.
INTERVIEWER: Where?
VIRGIL: My aunt has one.

In 1969, this exchange was, of course, hilarious—the very idea that someone's aunt might have a "high-speed digital electronic computer"! From a vantage point of just over four decades later, the joke is lost. Children have
computers—in fact, children are generally perceived as more likely to be familiar with computers than their elders. But by the same token, their elders also have computers. I am in my 50's; I have an aunt; and she has a computer.

What has taken place in these past forty years? The technological sea change in computing has been accompanied by a cultural shift as well. Computers are still industrial, or governmental, or scientific devices; but they are also part of the day-to-day lives of people of all ages and in all walks of life. There are many debates that we might still have about (e.g.) whether children should learn to program, or whether people's lives have been sufficiently changed for the better by these devices. Nonetheless, it can't be denied that the use of computing has been democratized over these past forty years, and the devices themselves have been (at least to some extent) demystified.

A similar change now has to take place for fabrication and construction devices. Just as computers had to overcome their original image as industrial-strength information-processing behemoths, so must fabrication and construction no longer be seen as uniquely associated with factories and industrial workshops. This paper is a discussion of where research and development will need to be done in order to realize and accelerate this cultural shift toward educational and child-friendly construction. In pursuing these themes, the discussion here will make use of several sample projects drawn from our own laboratory; but the emphasis of this paper is not so much on particular research projects as on several larger themes that are still underrepresented in discussions of children's fabrication. Specifically, the themes that will be explored here are:

(a) The types of physical materials in which children construct, and how technology can influence the choices and affordances of these materials;
(b) The increasing range of educational subject matter to which children's construction can be applied; and
(c) The range of physical and environmental settings in which children's construction and fabrication projects may be undertaken.

In part, the purpose of focusing on these themes is to expand the discussion of children's fabrication beyond the "standard", reflexive images. Certainly, it would be possible (say) to put a 3D fabricator into shop class, or to assign children to create one geometric shape on a paper cutter as part of a larger assignment. Such steps would not be objectionable, but they would still reflect an unfortunately narrow view of the way in which physical design and fabrication can be woven into children's lives. Construction, and physical creation in general, are now poised to blend with symbolic, linguistic, and abstract areas of education in ways that promise to benefit both sides of the traditional "mind/hand" dichotomy.

The following section of the paper explores, in turn, the ways in which materials, subject matter, and physical settings can respectively play into the cultural shift toward educational fabrication and construction. In the final (third) section we situate this discussion in terms of longstanding educational debates about "hands-on" learning in the form of educational crafts, and the meaning of "vocational training".

The Changing Culture of Children's Fabrication

Materials to Build With

Imagine a building project in which a sixth-grade student wishes to make a series of meshed gears. This hardly seems like an outlandish project idea for a student of that age—gear trains are good illustrations of both mathematical ratio and energy conservation. (In fact, there's a famous passage from Papert [5] in which he traces his own intellectual history back to an early love of gears.) The problem—at least up until a few years ago—is that it's hard to make a working gear for oneself. After all, cutting a gear with scissors out of paper—or even thick cardstock—is both time-consuming and requires high precision. And it's ultimately futile, anyhow: a cardstock gear won't last long in an actual physical device. As the three little pigs found out in the classic fairy tale, the right materials matter.

What are the right materials, then? Making a gear out of wood is a better choice— but a sixth grader would have to be a remarkably skilled and patient woodworker to accomplish the job with hand tools. The upshot of all this is simply that—until recently—constructing a gear train would be precisely the sort of thing that an interested student couldn't do. He or she would have to (in this case) purchase a set of pre-made gears: not a dreadful solution, arguably, but something is surely lost. But as it happens, a desktop laser cutter can now produce many high-
precision wooden gears swiftly: a series of (say) six gears, given the appropriate software, could be designed and cut out in a matter of minutes. What used to be an unthinkable project is now straightforward.

The purpose of this example is merely to point out that educational construction is deeply interwoven with choices of materials--and depending on those choices, certain projects either become "typical" children's activities, or else they are perceived as off limits. Historically, paper, felt, and yarn have been seen as child-friendly materials. Now, with the advent of computer-controlled fabrication, a host of new materials have entered the child's workshop. Acrylic is a good example: it is easily laser-cut, sturdy, non-toxic, and comes in a host of bright colors (perfect for a classroom display); in fact, along with those bright colors, it can also be purchased in transparent (or translucent) form, which makes it a plausible replacement for some projects that, in an earlier era, could only have been attempted in glass. Just outside our own lab, we have posted a couple of beautiful mathematical linkages, made in acrylic (by an undergraduate student) with the use of our lab laser cutter; these linkages have been on display for several years now, and have withstood manipulation by passers-by in our building for that whole time. Laser-cut acrylic can thus make a classroom wall (or child's room) into something approximating a "science museum"; the objects that a student produces can both look professional and remain usable for years.

Wood, of course, is the archetypal material for laser cutters; a desktop cutter can't be used on thick pieces of lumber, but it is ideal for slicing precise patterns in thin sheets of (e.g.) basswood or cherry. One might argue that wood, as the stuff of shop class, has after all been accessible to children for many decades. This is true; but as our gear example shows, fabrication tools not only increase the child's repertoire of materials (as with acrylic), but they also make possible a variety of new projects suited to older materials. It wouldn't be possible for most children to fashion wood into working mechanical toys or mathematical models of the sort shown at right in Figure 1 without the aid of a laser cutter. Indeed, the laser cutter can make possible new forms of paper crafts: a laser cutter can produce (say) tessellations or fractal cuts in paper that could never be done with a scissors in math class.

Thus far, our discussion in this section has focused on materials that can be cut with a desktop laser cutter: acrylic, wood, paper (we could also have mentioned textiles). Other fabrication tools introduce still more materials. Most 3D printers produce objects in ABS plastic (the same material used to construct Lego bricks); one type of 3D printer that we have in our lab produces objects in plaster. Inexpensive computer-controlled desktop milling machines can be used to create models in wax, styrofoam, or aluminum. In short, then, the things that children can make--and the types of stuff that they can safely work with--have burgeoned in the era of the home (or school) fabrication device.

Figure 1. Two projects involving the laser cutter, from our laboratory. At left, an acrylic linkage depicting an ellipse-drawing mechanism. At right, a wooden "slice-form" ellipsoid made of separate flat pieces of laser-cut basswood.
Subject Matter for Fabrication

From the standpoint of an engineering teacher or lab designer, there are obvious uses for educational fabrication. Certainly a student interested in mechanical engineering would benefit from the ability to create gears, cams, linkages, and so forth out of wood or plastic; more ambitious mechanical projects, such as playful automata or "Rube Goldberg" machines, become much more achievable as well. A student of architecture can make (or extend) models of her designs with the aid of a 3D printer; indeed, model-making often plays a prominent part in architectural education, and the addition of fabrication tools can extend that practice significantly. In a similar vein, civil engineers can make more accurate or appealing models of (e.g.) bridges, dams, and roads.

These, as noted, are straightforward uses of educational fabrication: they apply to those subjects or courses where construction has always been a traditional part of the curriculum. But one of the fascinating features of novel technologies is that they often cause us to reassess earlier traditions: new technologies can sometimes reveal the arbitrariness of previous practice. Nowhere is this more starkly apparent than in educational fabrication. After all, why shouldn't construction or design play a role in all sorts of educational enterprises?

A professor of history, for instance, might now devise a classroom project in which students use fabrication tools to create a model of the Acropolis: where formerly an assignment of this kind would be either hopelessly optimistic (or perhaps would produce a depressingly amateurish display), it would now be within the powers of students to tackle such a project with beautiful results. That same professor might have students use fabrication tools of various sorts to make small models of historical artifacts of all kinds: Roman aqueducts, suits of armor, Gutenberg's printing press, Babbage's difference engine, the Wright flyer. Just to inject some personal experience here: on several occasions over the past five years, I have co-taught (with my wife Ann) a course for first-year engineering students on the designs of Leonardo da Vinci. In that course, we have the students look through Leonardo's notebooks and study his engineering ideas; then the students use the fabrication devices in our lab to create working prototype models of Leonardo's designs. (Some of Leonardo's designs—for flying machines, for instance—were in the nature of "thought experiments". In many cases, even for entirely workable ideas, though, da Vinci himself was unable to create a model since he didn't have the resources or time to do so; our students can now, in effect, realize at least some of the dreams of the great Renaissance engineer.) The da Vinci course is taught as an engineering projects course; but with mild alterations, one could imagine a version of this course tailored to teach history students about Renaissance technology.

Figure 2. At left, a model of a tree printed out (in plaster) on a 3D printer by a team of undergraduates working with our laboratory [1]. At right, a model of a Renaissance-era paddle boat created for the "Leonardo da Vinci" engineering course mentioned in the text. In the boat, the gearing has been produced in plastic on a 3D printer; the hull of the boat is made from laser-cut wood and acrylic.

A 3D printer—to focus for the moment on this one exemplary fabrication device—need not be seen as the exclusive property of an engineering laboratory. Consider, by comparison, the standard laser printer: just as this device is employed across all disciplines in writing papers, the 3D printer can be used to conduct experiments and explorations in physical design. A teacher of literature might have his students print out a model of the streets of St.
Petersburg in the time of Dostoyevsky; a botany professor might ask her students to print out models of different branch patterns of trees (see Figure 2, at left); a chemistry instructor might have the students print out models of crystals or proteins; a mathematics teacher could decorate the classroom with gorgeous polyhedral forms; a teacher of dramatic arts might have students print out models for the set design of famous historical theatrical productions.

These are just a few randomly chosen examples of the myriad ways in which physical design and fabrication could easily be integrated into classroom education. Moreover, the use of such devices needn't be limited to schools. After all, many students now have an inkjet or laser printer at home; in the foreseeable future, families may have working 3D printers as well. (The prospect is no more laughable, after all, than the idea that in 1968 one's aunt might someday have a computer at home!) Should students eventually have "home fab labs", the prospects for integrating physical construction into personal crafts—and, for that matter, online or distance education—are extraordinary. Even at present, a student can go to websites such as thingiverse.com [6] and download files corresponding to printable physical models; in the future, such websites might accompany course materials in much the same way that many current textbooks are associated with online simulations, problem sets, games, animations, and videos.

Physical Settings for Educational Fabrication

The point just mentioned in the preceding paragraph—that "educational fabrication" need not be exclusively equivalent to "classroom fabrication"—is really a prelude to a more far-reaching reconsideration of the physical and environmental settings for constructive learning. As fabrication becomes more affordable, flexible, and versatile, one can imagine all sorts of arrangements and settings in which children's design and building can take place.

We might start with the larger-scale end of this landscape. Currently, there are a variety of commercial businesses that offer fabrication services—particularly when the scale or materials of construction are beyond those available even to a well-equipped college laboratory. Fabrication in metal, for example, is possible—but the cost of a 3D printer that can work in metal is far greater than that for a plastic printer (and that cost is likely to remain high for at least the near-term future). A commercial service for metal printing thus essentially rents out the use of such a printer for a specific project, charging the user in addition for the cost of materials. Students who wish to create a high-resolution construction in steel, then, are able to first print a "rough draft" in an inexpensive material before sending out the construction file to a service for the final, finished version. Plausibly, such services may proliferate in the near future as students and hobbyists begin to work with physical construction in greater numbers: one could imagine that physical fabrication will take its place within commercial office copying centers, so that (e.g.) a large-scale poster or billboard and a working metal machine might both be "printed out" at the same location. Commercial services might also be able to print out very large items (e.g., for theatrical sets, or front yard displays) that are impractical for personal fabrication devices.

Along with large-scale services of this type, we may also begin to see increasing experimentation in "special-purpose" printing for particular settings. A science museum, for example, might allow children to print out their own fanciful animal designs for a participatory diorama, or perhaps visitors could print out geometric pieces to assemble into a larger model of a crystal. Art museums, public playgrounds, outdoor malls, and so forth might have their own exhibits or displays in which users can participate by printing out customized elements: just to suggest another example, one might imagine children printing out scenic figures for a model railroad or a holiday display.

Beyond these special-purpose fabrication sites, it is not unreasonable to imagine increasing exploration of portable or small-scale personal fabrication. After all—as we have already noted in this paper—there are striking parallels, at least so far, between the history of personal computing and the history of personal fabrication. In both cases, we have seen a shift from industrial-sized machines to personal machines for students and hobbyists. Following this parallel development into the future, we might expect that—just as desktop computers gave way to laptops, netbooks, e-readers, and programmable phones—desktop fabrication could give way to small handheld devices for informal or small-scale printing. Children might print out trinkets, game pieces, construction kit pieces, and the like using portable 3D printing devices. As such devices come into existence, we might well see activities involving printing situated in playgrounds, parks, camping grounds, and school buses—in short, anywhere that children congregate or spend time. (An extended argument along these lines can be found in [3].)
Educational Fabrication and Educational Debates

In the previous section, we sketched several key arguments about children's fabrication:

(a) The advent of personal fabrication devices will vastly increase the range and sophistication of materials with which children can work, and will likewise expand the range of construction activities that children can undertake:
(b) Thoughtful and tasteful opportunities for fabrication and construction can be found in virtually all types of subject matter, and throughout school curricula from elementary grades to graduate school;
(c) The opportunities for fabrication will, over time, be increasingly widespread, ranging from high-priced special-purpose or large-scale efforts to informal projects done in a wide variety of settings.

In this section, we take a step back from these arguments and briefly explore their implications for two (occasionally contentious) issues in educational research.

Children's Crafts and "Hands-On" Learning

Fabrication devices such as laser cutters and 3D printers raise potentially thorny questions for educators interested in the role of "hands-on" learning and children's crafts. There are robust traditions of children's papercrafts (e.g., making origami figures or cutting out paper dolls), string and yarn crafts (making "cat's cradles", potholders, and the like), and woodwork (the traditional "shop class" of twentieth century education). Fabrication tools challenge these traditions in what might be troubling ways. For instance, one might ask whether a student who uses a computer-controlled laser cutter to shape wood–as opposed to using a saw or hand drill–is really getting the benefit of "hands-on" education. After all–to continue the argument–this student hasn't really put his hands on the material in the process of cutting it; might this not be yet another step in the distancing of children from actual physical materials?

There is no easy answer to this question, and no hope of resolving it in a short discussion here. Still, there are several preliminary responses that deserve mention. First, it should be noted that children have always used "high technology" in working with materials–it's simply that what counts as "high technology" varies from era to era. Even hand tools, ancient as they are, represent a huge advance over Paleolithic implements; and the desktop machine tools of the late twentieth-century craftsperson (band saw, power drill, and so forth) are themselves "high technology" in comparison to the tools available a century earlier. The point here is simply that fabrication devices represent yet another chapter in what has been a continuing story of increasingly powerful children's technology; the questions that we ask about (say) laser cutters are similar to those that might be asked about children's use of glue guns, handheld electric drills, or scroll saws.

Second, for those educators who place particular value on hands-on learning, it should at least be considered that the advent of computer-controlled fabrication gives children new powers and opportunities for construction. Thus, the amount of time that children spend in hands-on construction could well be increased in both quantity and quality by the use of these new devices. Or, to put the argument another way: if children are denied the use of these devices, they may perceive a gulf between the "real" world of adult technology and construction, and the less-than-serious "toy" world available to them. In the worst case, many children in this situation might simply spend less time in hands-on learning activities altogether.

Finally, and more generally, what is really needed here is a larger, more thoughtful, more historically grounded theory of children and technology–a theory that gives us some understanding of the role of physical materials and multisensory input in children's education. Perhaps it matters, in some cognitive sense, whether children work with a hand saw, a scroll saw, or a laser cutter in fashioning wood; or perhaps it doesn't. But in any event, this very question is made far more urgent and pointed by the rapid advent of fabrication devices.
Vocational and Liberal-Arts Education

In my own view—it's necessary to enter the first person here—the longstanding division between "vocational" education, with its emphasis on construction and mechanical skills, and "liberal arts" education, with its emphasis on intellectual abstraction, has been disastrously counterproductive for both camps. Arguably, this is a division with a long pedigree—one can trace the divide at least as far back as the ancient Greeks, for whom manual labor (as opposed to higher philosophy) was primarily the province of slaves. This implicit gulf between the (exalted) world of the mind and the (somewhat less-than-respectable) work of the hand has retained much of its power to this day, as in the division between engineering and liberal arts curricula on many university campuses (including my own).

Again, this dichotomy harms both educational "tribes". Construction and design, as argued earlier in this paper, can play a wonderfully creative role in the study of the natural and social sciences, in the fine arts, in history, and in literature. At the same time, the ("vocational") skills of building and working with materials are valuable in designing scientific instrumentation, recreations of historical artifacts, theatrical sets and costumes, and a myriad other essential physical components of liberal arts disciplines. Mind and hand are fundamental and complementary ingredients of human endeavor, and this should be reflected in our educational philosophy from kindergarten on up. (A thoughtful, informative discussion related to these issues can be found in [2].)

There is some reason for optimism that the coming explosion of fabrication will play a role in dissolving this pointless, anti-intellectual divide. Conceivably, as students begin to construct and design with much the same fluency that they now bring to the written word, we will see curricula that integrate symbolic and tangible activities. Students in physics might build their own experimental apparatus; students in archaeology might make their own models of structures such as Stonehenge; students in psychology might design customized optical illusions; students of music might design their own instruments. Over time, perhaps, we might even do better than see fabrication play a role in the education of traditional disciplines; rather, fabrication can begin to refashion, to reconstruct the disciplines themselves.

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