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3D printing for children: What to build next?

Michael Eisenberg

Department of Computer Science and Institute of Cognitive Science, University of Colorado, Boulder, USA

A B S T R A C T

The era of affordable 3D printing is clearly underway; indeed, the historical patterns of growth in 3D printing are, in many ways, strikingly similar to those associated with the growth of home computing in the late 1970's. One of the prominent areas of increased interest in 3D printing is in the realm of education: fabrication tools are becoming available to college undergraduates and high school students, and even to younger children. Accompanying this burgeoning growth, however, there is an acute need to consider the ways in which 3D printing should develop, as a technology, in order to accommodate the abilities and activities of youngsters. This paper discusses a number of technological challenges to be overcome in making 3D printing truly available to children over the next decade. The most prominent challenges described here include: (a) expanding the range of physical media available for printing, (b) incorporating ideas derived from "pick-and-place" mechanisms into 3D printing, (c) exploring methods for creating portable and ubiquitous printing devices, (d) creating tools for hand-customization and finishing of tangible printed objects, and (e) devising software techniques for specifying, altering, and combining 3D elements in the context of printing. By facing these challenges, we can provide children (and adults) with a remarkably powerful and expressive means for creating all sorts of personalized artifacts.

1. Introduction: the emergent era of 3D printing for children

Three-dimensional fabrication–or 3D printing, as it is often called–is clearly a (if not *the*) technology of the moment. For those of us who have been fascinated by this technology for more than a few years, there is something almost disorienting about the suddenness with which 3D printing has captured public attention. Articles in the popular press note that hobbyists and professional users are now able to design, download, and print out a wide (and quickly growing) range of physical objects. One recent New York Times blog entry referred to the technology as "Industrial Revolution 2.0" and notes that it "will change the nature of manufacturing" [1]; an article in the same newspaper, published a little over two months ago, announced "a show of objects as assorted as a lacy chair, a prosthetic limb and a necklace of big white whistles" at Material Connexion in New York [2] A tone of similar excitement can be found in recent articles from (among numerous others) the BBC [3], Wired.com [4], and the *Atlantic* magazine site [5].

While there are several plausible reasons for this sudden burst of excitement, perhaps the most prominent of these is the recent availability of low-cost 3D printers such as the Makerbot [www.makerbot.com] and (recently-released) Cube [cubify.com/cube]. These devices, along with a variety of somewhat more expensive printers, now permit "ordinary" users to create their own objects at home. Typically, these are small-scale objects, printed in plastic; and thus, for now, the typical hobbyist is limited by the size and material of the current devices. Nonetheless, for the more ambitious, there are web services such as Shapeways [www.shapeways.com] and Ponoko [www.ponoko.com] that allow users to send off specifications for printing on (more "professional-scale") devices that work with other materials, such as metal, and with larger print-sizes. Though "revolution" might be an overused word in technological writing, it is fair to say that we are indeed living through the early phase of a wide-scale revolution in tangible creation.

There are eerie historical echoes here, in the rapid rise of public interest, between 3D printing in the early 2010's and home computing in the late 1970's. Indeed, the two technologies share similar historical patterns in more than this. In both cases, the technology began with large, expensive machines sold to a highly select group of industrial (or perhaps governmental) customers; here, the parallel is between the mainframe computers of the 1960's and the expensive stereolithography devices of the late 1980's and early 1990's. In both cases, this early "mainframe" period was followed by a brief but significant phase in which the devices became available at lower cost to university labs and small businesses; in the case of computers, this brief period was characterized by "minicomputers" in the late 1960's and 1970's, while in the case of 3D printing, this period was characterized (in

E-mail address: Michael.Eisenberg@Colorado.EDU.

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the past decade) by mid-sized workshop-scale 3D printers. And in both cases, the ''minicomputer'' phase preceded an explosive growth of experimental, accessible devices aimed initially at the hobbyist community and, still a bit later, at a wider audience of home users. (See also [6] for a similar comparison.)

For the purposes of this paper, there is still another striking parallel between computing and 3D printing that is worthy of attention: in both cases, the advent of home-accessible devices has sparked an interest in the use of the given technology by children. It is worth recalling how strange it seemed to many observers, back in the 1970's, that children–kids!–might actually use computers. The idea sounded almost absurd, as if someone today were to suggest that children could be given control of a high-energy collider. Books such as Seymour Papert's [7] *Mindstorms* and Robert Taylor's edited collection [8] *The Computer in the School: Tutor, Tool, Tutee* articulated the changing mood of the times, as researchers began to re-imagine computers in children's hands, whether as artificial tutors or (in Papert's much more interesting vision) as programmable devices.

One anecdote about this period will have to stand in as representative of the era. In John Markoff's [9] excellent book *What the Dormouse Said*, about the dawn of the home computer industry, Markoff relates the experiences of Bob Albrecht, a former Honeywell engineer who began teaching Denver high school students to program in Fortran (and then Basic) on a CDC 160 minicomputer in the 1960's. Markoff writes:

''Albrecht took his class on tour, at one point accompanying some of the students from the original Denver school to a National Computer Conference meeting. There they demonstrated their programming skills on the CDC 160 machine, shocking the high priests of computing. At the general conference meeting, there were subsequent complaints that someone had even considered turning children loose on computers!'' [p. 181]

Given the hindsight of almost half a century, it now appears quaint that people once thought of computers as off-limits to children. Indeed, in the current era computation (in the form of iPhones, iPods, online gaming, and so forth) appears to be disproportionately associated with youth culture. One might debate whether this development has been an unmitigated benefit to children's lives, but it is arguable that a similar cultural shift is now repeating itself with 3D fabrication technology. It is plausible, in other words, that a decade or two from now, it will seem odd to imagine a previous time when children were not thought ''ready'' to print out objects of their own.

A variety of provocative research efforts in ''educational fabrication'', bringing 3D printing (and fabrication in general) into classrooms, have been or are being pursued. (Cf. [10,6]) A position paper by Berry et al. [11] focuses on the use of fabrication technology in engineering classrooms, allowing students to design and experiment with physical objects more readily; the paper concludes,

''Engineering and technology associations should collaborate with educational associations to explore ways in which design principles based on digital fabrication can successfully increase teachers' engagement with engineering, mathematics, and related competencies. This exploration should also examine ways in which increased teacher engagement and competence may produce a positive impact on students, boosting their performance and engagement with engineering and mathematics''.

Three-dimensional fabrication for children need not, of course, be uniquely associated with classrooms; children don't, after all, spend all their time in classrooms. There are all sorts of other activities, and aspects of children's culture, that might be strongly affected over the next decade by 3D printing. Again, the parallel with computing is worth keeping in mind here: children use computers both in and out of classrooms, and for all sorts of purposes relevant to their own lives and interests. As designers, then, it is worth keeping in mind a broad perspective about how to create novel fabrication tools and projects for children. There are all sorts of possibilities that one might speculate about:

- Children might want to print out construction kit pieces, or to print out ''specialty pieces'' to use in conjunction with existing commercial construction kits.
- Children might print out party favors, charm bracelet elements, items of model railroad scenery, dollhouse furniture, game pieces, and many other customized small items.
- Children might print out items (e.g., customized souvenirs) at special settings such as museums, circuses, children's theater, or zoos.

These are rather straightforward examples, based on the sorts of activities in which children currently engage. A more pedagogical focus might center on children's creation of items such as chemical models, dioramas, mathematical models, scientific instruments or demonstrations, and so forth. (See [12,13] for more extended arguments along these lines, and [14] for an example of 3D printing for children in a museum setting.) It's possible to venture still more futuristic scenarios, in which children have the tools and materials with which to create or personalize their own furniture, musical instruments, or sports equipment.

The point of this discussion is to whet, in the reader, a realistic sense of optimism and enthusiasm about the cultural and intellectual potential of children's fabrication. Still, it must be admitted that, to date, we haven't achieved this vision. The remainder of this paper, then, is devoted to a discussion of where designers should concentrate their energies in bringing 3D printing, productively, into children's lives. The intent here is to spark exploration of fabrication beyond the boundaries of the current marketplace, focusing on the interests, capacities, learning opportunities, and day-to-day culture of children. The current state of 3D printing, exciting as it clearly is, is still missing a variety of features that would make the technology useful in learning and development; there is much to be done, and it is this community (of educational technologists) who collectively need to do it.

The following section of this paper is divided into five subsections, each of which focuses on a particular promising area of development for children's 3D fabrication. In the final (third) section we take a broader look at these areas (and a few others still to be explored), in the context of how 3D fabrication could come to impact children's lives and learning.

2. Five challenges for designers of 3D fabrication systems for children

In this section, we unpack the promises of the previous paragraphs, and explore a variety of potentially fertile areas for innovative design in 3D printing for children. These areas, which we will examine in turn, are:

(a) expanding the range of physical media available for printing,

(b) incorporating ideas derived from ''pick-and-place'' mechanisms into 3D printing,

(c) exploring methods for creating portable and ubiquitous printing devices,

(d) creating tools for hand-customization and finishing of tangible printed objects, and

(e) devising software techniques for specifying, altering, and combining 3D elements in the context of printing.

2.1. Expanding the range of physical media available for printing

Perhaps the greatest current limitation of (currently affordable) 3D printing is in the material used for construction. The most common printers currently available for home use print out objects in ABS plastic.[1] As construction materials go, ABS is versatile: it is strong enough so that one can (e.g.) print out small working mechanical devices, fairly resistant to scratches and dents, and melts only at very high temperature (i.e., it will not soften in hot weather). Nonetheless, ABS plastic, like all materials, has limitations or disadvantages for particular uses. For example, it is an insulator; thus, if one wants to print out a conductive object, ABS plastic is inappropriate to the task. It is not quite strong enough to (e.g.) withstand extreme weight or stress: one would not create a large-scale working robot out of ABS, nor a stepladder, nor a serious piece of furniture. There is some debate (see [15]) about how seriously ABS plastic is susceptible to degradation in sunlight, but it is probably safe to say that one would not want to construct an ABS object for long-term outdoor use if the consequences of a loss of strength were meaningful.

More generally, from the standpoint of children's activities, there are still other limitations. Consider, for example, the issue of printing out objects in color. Our lab's Dimension SST printer (a common model) only prints out in one color of ABS plastic at a time: there are several colors of plastic available for printing, and one might plan to make multicolored objects by (e.g.) swapping the various color-plastic cartridges in and out of the printer during a single job, but in general one tends to simply print out an entire object in a single color. By printing out an object in white ABS plastic, one can then paint the finished object with acrylic paints (see, for instance, Fig. 1), and often this is perfectly fine for a given project. Still, one might wish to have a different "look" for an object than that of painted ABS plastic.

Thinking about printing multicolored objects, then, leads us to think more generally about the aesthetics of printed objects. Children might wish to print out (say) models of natural forms: trees, flowers, insects, birds, reptiles, mammals; they might wish to print out metallic-looking pieces for charm bracelets, or objects that look like brick or stone for model buildings. Can we design printing materials that are appropriate—in texture, in color—for projects such as these? We will return to these issues in later subsections, but the larger point here is that the *materials* of 3D printing should be developed with an eye toward the types of printing projects that might be compelling for children's educational and creative interests.

One recent interesting development along these lines is the creation of a commercially-available 3D printer for chocolate [16]; an early example of printing in this material was described in an influential paper by Malone and Lipson [17]. Chocolate has (vastly!) different affordances for children's projects than does ABS plastic, and the existence of a printer of this sort might suggest still other types of 3D printing for kitchen crafts, edible and otherwise: printing in cake icing, printing specially-shaped candies, printing pieces of gingerbread houses, printing out cookie molds, and so forth.

There are many other types of materials for children's activities that are worth investigating. Again, the paper by Malone and Lipson [17] is a wonderful source of inspiration here, mentioning the possibilities of printing (for example) in wax; at least one commercial (professional-level) 3D printer [www.solid-scape.com] makes use of a "wax-like" proprietary material for printing. These efforts suggest the strong possibility of developing a device for printing in multi-colored (crayon-like) wax for children's constructions (e.g., insect models, or candles), or for creating a system with which children can print out their own wax-like forms for casting in molds. Yet another line of thought would be to explore printers that combine multiple materials appropriate to children's projects: devising printers, for example, that could embed conductive wires, magnets, or RFID tags at designated locations within solid objects, in order to create projects that dovetail with computational control.

To sum up: the current state of home (or hobbyist) 3D printing, with its emphasis on ABS plastic as a material substrate, represents only an early step in encouraging the growth of a "children's culture" of 3D printing. Materials with different textures or aesthetic affordances, materials for (e.g.) kitchen and food crafts, materials for casting, and combined materials for electronic projects represent just a few areas for experimentation in expanding the range of children's printing.

2.2. Outputting discrete "voxels"; bringing pick-and-place mechanisms to children's printing

The discussion of the previous subsection focused on varying the material substrate of 3D printing; but, by and large, we assumed that the *mechanism* of printing, via layering of a "soft" material such as plastic or wax, would be unchanged. A more radical experiment would be to rethink 3D printing less in terms of producing continuous, "analog" 3D output, and to create devices that print out constructions composed of numerous small discrete units.

There are existing children's materials that suggest the sort of idea we are proposing here. Perler beads [perler.eksuccessbrands.com], for example, are small multicolored beads that are typically used as "pixels" to compose two-dimensional pictures; though a perusal of Perler bead images on the Web will reveal the occasional three-dimensional construction as well. Perler beads are shaped as small hexagonal prisms, and (when joined together into planar or volumetric constructions) are joined together by heating. Fig. 2(a) shows a Perler bead construction made in our lab (by hand): here, the bead elements serve as "voxels" in a representation of an urn. The photograph in Fig. 2(b) shows a construction made from an alternative construction material: PixOs [www.pixos.com], which are multicolored spherical beads joined together in constructions via moistening.

Again, the typical construction with these materials makes use of two dimensions only, so that the beads are employed as "pixels". Indeed, several other child-friendly materials, such as one-by-one Lego bricks and multicolored candies (such as M-and-Ms) are used in similar ways: a Web image search on "Lego pixel art" or "M and M pixel art" is certain to yield amazing results. Moving from "pixel art" to "voxel art" in unit materials is more challenging, and more prevalent in some materials than others.

A natural exploration for children's 3D printing would be to create devices whose operation is used to assemble patterns of unit voxels into partially or totally finished constructions. We might imagine a machine that – given a suitable object representation from a computer – would discretize that object into voxels, and then sequentially place the voxels, layer by layer, to produce a 3D object. The operation of such a hypothetical device would be close in spirit to the "pick and place" machines that are used in factories to rapidly place digital electronic elements onto a circuit board. (See also [18] for a discussion along similar lines, likewise making use of beads as a sample material.)

Briefly, the essence of a "pick-and-place" machine is to do what the name suggests: to retrieve elements (such as resistors) from a source of many such elements, and to use a mechanical placement element (rather like a claw) to place the element in a precise location on a two-dimensional surface. Our own imagined version of this device would consist of numerous sources of (e.g.) beads, arranged by color; the pick-and-place machine would rapidly take a single bead of a specified color, place it in a particular location on a plane, and then repeat that action until a full plane of beads had been placed. Then, the machine would move on to the next higher

[1] "ABS" is an abbreviation for "Acrylonitrile butadiene styrene".

Fig. 1. Polyhedral sculptures (of a penguin and pineapple), designed and printed in the author's lab (in plastic) and decorated with acrylic paints by A. Eisenberg.

Fig. 2. Figures created with physical ''voxels''. At left (a): an urn of Perler beads, created by J. LaMarche. At right (b): a bottle-like shape composed of PixOs, created by J. Meyers and M. Eisenberg with the use of a pre-existing negative mold.

layer, placing beads in specified locations atop the layer that it had just completed. In this fashion, layer by layer, we could imagine a device putting together a shape like the one in Fig. 2(a).

Several observations are worth making about this scenario before we turn to still other possibilities. First, it might be argued that a device like the one suggested here actually diminishes rather than enhances children's constructions: rather than (e.g.) patiently assembling Perler beads by hand into larger forms, we are suggesting that a desktop machine ''print out'' such forms automatically. The issue here is indeed a serious and complex one: our goal, as designers, should be to expand children's horizons for printing, not to render their construction work completely automatic. There is no simple answer to this question, though we might note that one possibility is to use a ''voxel printer'' of the type suggested here to print out only *partial* constructions (e.g., ''platforms'' for other 3D constructions) rather than entire forms. That is, a child might create a construction that is partly printed, partly assembled by hand. In this vein, we might note that some types of 3D constructions would simply be too complex, or tedious, for most children's work; thus, a voxel printer might allow children to create far larger or more interesting forms than they would otherwise have attempted.

A second observation is to note that the discussion here could be fruitfully combined with the discussion of alternative materials in the previous subsection. For example, we might imagine a children's printer that works in mixed materials, printing out (say) a sculpture core of discrete voxels and then covering that core with layered material of a softer type. Alternatively, the type of printer mentioned earlier that employs (say) small magnets or electronic components as portions of printed forms might be structured as a ''pick-and-place'' device for these specific elements, placing them within outer constructions made of soft materials.

Finally, it is worth noting here the resonance between our discussion of ''pick-and-place'' machines and the discussion of the opening paragraphs of this paper. We noted earlier that both computers and 3D printers have experienced a similar historical arc, in which an expensive industrial technology is finally assimilated into children's activities. We might imagine, then, that industrial pick-and-place machines could likewise exhibit the same historical pattern: as of now, pick-and-place machines are expensive factory-floor devices, but their essential purpose and operation could be customized for the interests of children and home users.

2.3. Portable and ubiquitous 3D printing

One of the striking developments in home computing since the late 1970s has been the steady move from a preponderance of desktop devices to a preponderance of small and portable devices: laptop computers, tablets, handheld devices and the like. It is at least conceivable that a similar evolution may occur in the realm of 3D printing, though the technological and engineering issues involved in this transition are significant.

An earlier paper by the author [19], written over four years ago, outlined some of the possibilities and hurdles involved in creating "pervasive fabrication devices". In that paper, several ideas were sketched–for example, placing devices for relatively rapid printing of (say) animal forms within zoos or science museums so that children could design and print their own animal model within the time span of a typical museum visit. Another suggestion included in that paper was to design very small printers, designed for objects such as charm bracelet elements, costume accessories, or party favors; these might be light enough so that children could tote them around, and the printed objects would be sufficiently tiny so that they could be printed relatively rapidly.

There are still other scenarios, at best only hinted at by the earlier paper, that could be imagined for portable or pervasive 3D fabrication for children. One might imagine, for instance, a child printing out a small unique (or personalized) object at a science museum that could then be place unobtrusively within a larger display (such as a diorama) at the site. If the child's object could remain on display for weeks (or months, or years), it could in effect create a "favorite spot" for the child to visit in the museum afterward. Another possibility might be to place a 3D printer that creates large, complex, or location-specific objects to be placed within a museum or public display: in this case, the child's role might be to add one tiny element or detail to a much larger construction. A variant of this idea would allow a child to print out – on a small, portable 3D printer – an object that could then be incorporated in real-time into a larger construction produced by a specialized, large-scale printer: for example, a personalized token printed by a child could be fed as input to a larger printer, which might then incorporate the token into a large printed surface.

The overall point here is that we need not think of 3D printers as purely "desktop" objects any more than we do computers. There are many opportunities to explore the creation of child-friendly printers in various locations and at various scales, ranging from small-scale "rough copy" printers to larger specialized public printers.

2.4. Tools for "post-printing" tasks: finishing, decorating, and embellishing

There is a crucial intellectual shift that is still waiting to accompany the growth of child-friendly 3D printing: we, as a community of designers, need to re-conceptualize these printers not as merely stand-alone artifacts but as elements in a larger technological ecosystem of devices and techniques. In other words: a 3D printer, on its own, is only capable of supporting certain types of children's projects. When combined, however, with a variety of still-to-be-imagined "accessory" devices and materials, the expressive range of 3D printing for children can be vastly expanded.

Consider – again, to return to our recurring analogy – the ways in which home computers have, over time, been enriched by devices and gadgets beyond the central processing unit. In the earliest days of home computing, children did not have (just to name a few objects) inkjet printers, tablet-based input devices, touch-screens, or "physical" sensing devices (e.g., such as the Wii or Kinect). In the classical terminology of computer architecture, all of these are "peripheral" devices, in that they serve input/output functions with respect to the central computational platform; but collectively they have had a tremendous impact on the range of projects that children can undertake. In short: when we think about "children's computing", we are really thinking about an interwoven collection of artifacts far beyond the classical notion of the "computer" alone.

In a similar vein, we now need to think of "children's 3D printing" as encompassing a potential ecosystem that expands and enriches the capabilities of the stand-alone printer. There are numerous ways we could approach this theme, but for the purposes of this essay we might consider the "post-printing" phase of 3D printing. Suppose, for example, we imagine that a child has interests in using a 3D printer to create realistic models of natural forms: birds, mammals, insects, reptiles, flowers, trees. As things stand, 3D printers aren't particularly good at such projects: one can create an ABS model of (say) a canary, but it won't look much like a brightly-feathered bird. Nor will a model of a giraffe, iguana, or dragonfly have the right texture or coloring; nor will a model of a pine tree or dandelion. In pursuing any of these projects, we run up against the need for decoration, texturing, and hand-embellishment of printed forms.

What sorts of devices or "peripherals" might assist in this process? We could imagine, for instance, devices whose role it is to "print out" textural coverings to accompany 3D-printed objects. Perhaps a specialized printer might be able to create patches of reptilian scales or mammalian fur in tandem with particular 3D models: this would enable the builder to add specialized surface textures to all or parts of objects. Or perhaps there might be "printers" for small-scale objects with leaf-like or petal-like textures to accompany the creation of botanical forms. Or we might concentrate on the range of decorative materials available for children: new paints, or coatings, or textures specifically geared toward enhancing printed plastic forms.

Yet another direction for research and design might be to create computationally-enriched handheld tools for decorating or embellishing: maybe a coloring device (a "responsive paintbrush") could be created that emits distinct colors of ink or paint in response to distinct surface textures. The idea behind a device of this kind is that one could first print out a subtly-textured form (e.g., for a beetle or flower) which can then be painted by our responsive paintbrush, creating (say) gradients or patterns of color on the 3D-printed surface. Or – just to take still another possibility – one might create a handheld "touching-up" device that can be used to etch or (partially) melt and perturb printed plastic objects by hand.

Again, the larger point here goes well beyond the feasibility of any of these particular ideas, or even the specific notion of "post-printing tools". The point is rather that 3D printing and fabrication needs to be imagined as the work of a "shop" or "studio", not merely a single device. For children's projects, it will be important for the design community (that is, us) to create all sorts of novel "stuff" – colors, textures, paints, gadgets, input and output devices, handheld tools – to match the interests of youngsters and the challenges of educational printing.

2.5. Software techniques for enabling children's 3D modeling and printing

The previous subsections have focused, for the most part, on the tangible and hardware aspects of 3D printing for children—expanding the range of "printable stuff", creating novel types of printing devices, and imagining a supportive "ecosystem" of supporting devices and physical materials. Nonetheless, perhaps the greatest obstacle to children's participation in the world of 3D printing is the difficulty of working with 3D modeling or graphics software (a difficulty not, of course, limited to children alone).

There are numerous lenses through which to view this issue. One important avenue is to create easier modeling tools and software—systems that are more "natural" or less conceptually demanding than traditional 3D graphics systems. In this case, the basic idea is to allow children to more easily define 3D elements suitable for printing. There are several current research projects along these lines [20–22], including a couple from our own lab [23,24]; collectively, these efforts hold promise for introducing youngsters to spatial modeling (and perhaps spatial and visual cognition more generally).

Rather than focus on 3D modeling per se, however, there are still other ways in which software can be improved for the purposes of 3D fabrication. Let us begin this reflection, for instance, with an observation that is likely to hold true for the foreseeable future: 3D printing devices are limited in scale. That is, it is unlikely that children will (at least soon) be able to print out objects of more than about one cubic foot; and affordable desktop printers, or portable printers, may allow only for much smaller printed objects than that. The result of this limitation is that, if children wish to print out moderately large objects, those objects will have to be printed in parts, rather than all at once.

What, then, does it mean to print out an object "in parts"? Depending on the project, there might be natural ways of "breaking up" a large physical object into printable units. A printed-out machine (e.g., a model of an engine) might be decomposed into an assembly of distinct mechanical elements; an architectural structure (such as a building) into stackable units; an animal into distinct morphological elements (limbs, trunk, head, etc.). In every case, the goal of creating physical pieces for assembly is one that confronts the modeler—and, crucially, this is not a goal usually associated with 3D *graphics* alone. To this writer's knowledge, there are no popular graphics software systems specifically geared toward the eventual task of assembling physical, fabricated structures. Just to pursue this thought a bit further with a specific example: imagine decomposing an animal model into portions that can easily be glued or snapped together once printed out. (The printed limbs, for instance, might have projecting "ball" units that could be snapped into "sockets" placed within the trunk.) This, again, is not a typical *graphical* decomposition, but is rather motivated by the tangible qualities of physical assembly.

There are still other software projects that could be undertaken to make 3D fabrication more expressive. One recurring issue in high-end 3D printing involves the need for including ancillary "support" materials in the printing process, to allow for the creation of complex shapes. (For example, on our own lab's Dimension SST printer [www.dimensionprinting.com], a plastic form with an "overhang" will inevitably be printed out with the aid of structural support material beneath the overhang. This material is later etched away, once the plastic has hardened, but its initial presence keeps the entire structure from collapsing during the printing process.) It might be feasible to design software that permits children to avoid the use of support materials by taking a complex shape and printing out individual simple (convex) pieces that can later be glued or assembled together. In essence, this would be a software-based approach to a problem that arises specifically because of the limitations of physical materials in printing.

Earlier in this essay, we alluded to the problem of printing multi-colored objects: our own lab's printer, for instance, can only output material in a single color at any one time. Thus, we might envisage a different kind of software project, enabling a system to decompose 3D objects into separate pieces that can be printed out in distinct colors. Thus, if a user were to design a multicolored 3D model of (say) a striped beach ball, the software could automatically create several distinct printable forms that could be created in their own distinct colors (several pieces in red, several in white, several in yellow, and so forth) and then reassembled into a single multicolored spherical form.

3. Fabrication for children: why now?

A natural response to the suggestions of the previous section might be to point out that they are hardly unique to children's needs. Couldn't adults use 3D printers that are portable, or that work with novel materials? Couldn't adults benefit from fabrication devices augmented by expressive post-printing tools? Certainly these would be welcome additions to adult-friendly, as well as child-friendly, fabrication. At the same time, focusing designers' attention on *children's* projects and interests seems to bring with it a tonic, less self-important attitude. Perhaps printing in playful materials (such as beads, or cake icing), or covering printed objects with strange new coatings, or carrying tiny printers about in the park, might seem a little frivolous for adult-oriented designers. Perhaps the attentions of those adult-oriented designers tend toward the "serious", "business like" applications of 3D printing–creating desk accessories, or small medical items, or plumbing parts, or items for car repair. These latter examples are worthy projects, but when it comes to sparking designers' imaginations, frivolity has some advantages. Designing for children leads us to think about aesthetics (can we make 3D printed objects more colorful?), about understandability (can we make the task of 3D modeling easier?), about safety (can we create new non-toxic coatings for 3D printed items?), and about cultural issues (can we create software interfaces through which children can swap, remix, and combine 3D-printed forms?). It is perhaps worth recalling in this context that the early industrial pioneers of computing were decidedly serious, non-frivolous people; and precisely because of their myopic concentration on the adult realms of business, the military, and management science, they failed to anticipate not only many *profitable* developments in technology, but also many *intellectually challenging* problems and research opportunities.

This observation returns us, once more, to the historical perspective. Throughout this paper, we have made use of a running analogy between the current technological moment in 3D printing and the dawning years of home (and child-accessible) computing in the late 1970's and early 1980's. Indeed, in the previous section, we took several prominent elements of that analogy – moving from "industrial-strength" to "child-friendly" devices, moving from "desktop" to "portable" devices, and so forth – and used those elements as springboards for re-imagining the coming generation of fabrication tools for education and play.

At the same time, it should be noted that the analogy between computing and 3D fabrication has a less cheerful side. For those who do not believe that the current spate of children's technology is an unmixed blessing, there may be an ominous note in trying to relive recent history all over again. Has the computer really been such a wonderful addition to children's lives? And – if the answer is "no" – do we really want to pursue an analogous path in introducing 3D fabrication tools into homes, classrooms, and other child-accessible settings? For those who view children's computing as (take your pick) wasteful, faddish, or educationally harmful, might the same adjectives be leveled at children's fabrication?

One, rather passive, answer to this question might focus on the likely inevitability of technological change; that is, regardless of one's own personal answer to the value of children's fabrication, its presence will be increasingly felt over the next decade. Those who argued against the value of computers in children's lives (see, for example, [25,26]) might have originally had valid points to make, but their arguments were in any event ultimately overwhelmed by historical events. Children now use computers – often at an early age – despite what any of the naysayers might have warned in the early-to-mid-1980's.

Fabrication is likely to have a similar aspect of technological inevitability over the next decade, but that does not mean that our own personal values are meaningless—particularly within the research and design communities. We, as designers, can fashion tools, materials, and settings for children that reflect our deepest values about the purposes of education and play. If we feel that there is a potentially ominous or unhelpful side to children's fabrication, we can work to alter or mitigate it; conversely, if we feel that there are especially beneficial aspects to the technology, we can work to make those aspects more prominent.

It is in this spirit that the suggestions of the previous section are offered. There are (in this writer's belief) extremely important positive elements latent within 3D fabrication—elements that can make a beneficial difference in children's lives, and that can counter some of the least helpful aspects of purely "virtual", screen-based technology. Where children's experience of the Web is now skewed (largely, though not exclusively) toward consumption – of animations, of commercial products, even of educational items such as lectures and lessons – the world of fabrication offers children an experience of self-directed construction. Where the world of the screen mutes or suppresses tactile experience, building activities highlight that experience. Where the world of social networks tends toward extroversion – placing children in a state of near-constant communication and social exchange – the world of construction tends more toward solitary, quiet, personalized, and introverted work. Where the world of applications increasingly situates artifacts "in the cloud", in some abstract and etherealized state, the world of construction situates children's artifacts on cabinet shelves, classroom desks, and bedroom walls, within plain sight.

In these respects, a move toward child-accessible fabrication can serve as a salutary counterweight to the current culture of children's technology—at least a slight swing of the pendulum in the opposite direction. But one scenario that we wish to *avoid* is a world in which construction becomes merely a push-button exercise; that is, we, as designers, need to create fabrication tools that enhance and extend the practice of construction and not cheapen it. Conceivably, one might create (say) fabrication tools that simply allow children to select a pre-designed toy object from a website and print it out at home; this is in fact a likely future scenario, but it's hard to argue that it greatly improves the lives of (at least materially well-off) children. In this author's view, tools of this sort simply feed into the larger cultural tide of thoughtless consumption.

The suggestions of the previous section are intended for a different purpose: to help envision a type of children's fabrication that is at once powerful, rich, and yet still challenging—that demands concentration, encourages creativity, and rewards expertise. By creating tools that enable children to build their own dioramas, scientific instruments, kinetic artwork, model railroad settings, doll furniture, tops, and myriad other objects—by creating tools, that is, that fit naturally within the most challenging and expressive areas of children's intellectual lives—we can create a version of fabrication that reflects our most hopeful portrait of human experience.

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