3D Printing: Making the Virtual Real

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> *The world has arrived at an age of cheap complex devices of great reliability; and something is bound to come of it.*
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> – Vannevar Bush, *As We May Think*, 1945

Introduction

A 3D printer uses a virtual, mathematical model to construct a physical artifact. For example, a designer in the process of creating a new laptop can use a software package to create a three-dimensional model of her creation, that can be manipulated and viewed on the computer screen. The 3D printer can take the symbolic representation of this new object and use it to build a full-size, physical model that can be held and manipulated, helping the designer to better understand the strengths and limitations of her design. An architect can turn the plans for a building into a three-dimensional model and then "print" a scale model to help him understand and communicate his design. An archaeologist can print duplicates of an important, but fragile, tool so that her students can hold it in their hands and better understand how it might have been used by an ancient civilization. A biochemist can print accurate models of DNA molecules, enlarged by many orders of magnitude, to help students and researchers better understand nature by engaging their hands as well as their eyes in comprehending the geometry of nature. And a student of the arts can create a unique object that would be difficult or impossible to build by hand.

Terms such as "3D Printing" and "Rapid Prototyping" tend to be used inconsistently throughout industry and academia. In this paper we will adopt the terminology proposed by Todd Grimm in *A User's Guide to Rapid Prototyping*:

> Operating in an office environment with little demand for training and oversight, 3D printers function as peripheral devices. … [c]ombining low purchase price and low operating expense…. [Grimm 2004, p 42]

These machines are at the low end in terms of cost and complexity of a larger class of machines called *additive*; that is, they create objects by building them up a layer at a time. We will not here consider other types of computer-controlled manufacturing, such *subtractive* machines, which work by cutting away from a larger piece of material in order to build a part.

Additive rapid prototyping machines were first introduced twenty years ago, when 3D Systems introduced the Stereolithography, or SLA machine. While these machines were remarkable for their ability to create complex parts, they were (and continue to be) large, expense, and difficult to operate. As such, they are of limited interest to most academic institutions except for a few well-funded laboratories. However in the late-nineties lower cost machines using technologies such as fused-deposition modeling (FDM) and powder binding (defined below) began to be available in the $30,000 to $50,000 range. These machines, which can be used without special environmental controls and with a modest amount of training, are the first 3D printers by our definition.

In the evolution of rapid prototyping equipment, we have seen a history somewhat like that of the mainframe computer (SLA) and the mini-computer (early FDM and powder binding) systems. However, we are on the verge of the introduction of new systems that will cost less than $10,000, require very little training, and are capable of being operated in a typical faculty office or computer lab or home. At least one vendor has the ambition of producing 3D printers for less than $1000 in five years [Desktop 2007a]. It is the thesis of this paper that as these printers achieve lower price points and accessibility, they will spring up across campuses and be used for applications yet to be imagined. Our purpose is to disseminate a basic understanding of a technology that is likely to grow dramatically in popularity within the next few years.

As 3D printing becomes more common across the campus, it will raise the issues typical with the dissemination of any new technology. Will a campus choose to standardize on one or a few technologies that it can best support, or will it allow users to select the technology they believe is best for their needs? Will central IT or other larger entities invest in creating 3D printing centers, or allow a fully decentralized model to develop? How will the material costs for 3D printing be allocated, a similar problem to that faced with 2D printing, but most likely at a much higher cost? Who will be responsible to assessing the environmental impact of 3D printers? While manufacturers strive to use materials that are as benign as possible, hidden health or environmental impacts could well occur in some cases. Anticipating some of these issues as 3D printers start to arrive on campus could ease the difficulties that come with the adoption of any new technology.

While the administrative impacts are important, the more interesting question may be the pedagogical impact of 3D printing. Modern media, and particularly the networked computer, have made accessing information via the two-dimensional screen ubiquitous. This has tended to overshadow and marginalize more traditional, tactical modes of understanding that exist in the three dimensional world. When a child encounters a toy block, she picks it up, looks at it, holds it, smells it, puts it in her mouth, perhaps knocks two blocks together to see what sound they make.

Compare that with the encounter with an image of a block on a two dimensional screen. While the computer has enabled many of use to see things we never could have seen before, such information may literally fall flat. Even an object displayed using a 3D display can't be touched and held. While haptic technology may hold out the promise of adding the dimension of touch to digital information, there is no substitute on the near-term horizon for gaining the knowledge that we gain by holding and manipulating an object and the information that we get from encountering a physical object in the real world. 3D printing offers a way to bridge this gap between the virtual and the real – thus its enormous potential for enhancing knowledge.

Furthermore, 3D printing allows a new way of creating never-before-seen objects, a new medium for artists and designers. As a new medium, 3D printing has a direct impact on what can and will be created. In the words of comic artist Scott McLoud, "The technology has ideas about the form the art should take [McLoud 2007]." Thus new technologies will always intrigue the artist. Once the creative community gets a chance to use this technology they will come to expect it and be unwilling to be without it, because of its potential to create new and different artifacts.

3D Printing: process and equipment

To use a 3D printer, you have to have something to print. In most cases, users create their models using a commercial CAD tool such as Solidworks or Rhinoceros. This complex software can be quite expensive, but as it has come into wide use academic licenses are generally available for several hundred dollars a seat. Occasionally lower-cost software such as SketchUp, available in free and in "pro" versions can be used, but with some limitations since SketchUp was not designed to create manufacturable objects. As lower cost printers become available, the software market is likely to broaden and new, simpler programs may become available, analogous to the drop in cost and complexity of desktop publishing software in the 1990's. Commercial 3D CAD software also places demands on computer processing power and memory, although the vast majority of the newer multi-core systems will be more than adequate for most modelers.

The current generation of 3D printers typically require the output from the CAD program to be stored in a format called STL, which defines a shape by a list of triangle vertices. This step is largely invisible to the user, although the output may need to go through an automated "clean up" step to reduce anomalies that might be invisible on a screen but could impact the printing process. Then the cleaned up STL file is used to drive the 3D printer.

3D printers work by building up parts layer by layer. Depending on the machine and the precision required, an individual layer is about 0.0035 to 0.007 inches thick [Grimm 2004, p. 167, p 170]. The size of an object that a particular machine can make is limited by a bounding box called its *build size*. For example, the powder-binder printers offered by Z Corporation have a build-size of 8 x 10 x 8 inches to 10 x 14 x 8 inches [ZCorp 2007]. There is considerable craft in aligning parts within the build area to achieve maximum quality and minimum build time. Depending on the technology used, the size of the object, and the precision required, build times can run from an hour or two up to twelve hours or more. However, once the build process begins, it generally requires little or no supervision or intervention.

While there are new technologies primed for release in late 2007, as of this writing the vast majority of 3D printers used in educational institutions are either fused-deposition modeling or power binder based. This section provides a brief introduction to two of the most common systems and their capabilities.

Fused-Deposition Modeling (FDM): Stratasys Dimension

FDM machines build layers by extruding a thin bead of a semi-molten plastic, usually acrylonitrile butadiene styrene (ABS) plastic. ABS is an attractive material, because it's hard, durable, and low in toxicity. It's familiar as the plastic used in Lego-brand toy bricks [designsite 2007]. Although it can be dyed, it's typically used in its original off-white form. The FDM machine heats the ABS to soften it; as it's extruded, it begins to harden and as it does it adheres to the layer below it. Because the material comes out soft at first, any "overhanging" parts need to have supports built into them; once the plastic hardens, the support material is removed.

The Stratasys Dimension sells for approximately $20,000 to $35,000. The Dimension has a build area of 8 x 8 x 12 inches. The least expensive Dimension systems require the support parts to be removed manually, while the more expense systems use a soluble material that's washed away in a solvent bath. FDM machines build strong, precise objects that can be used for a wide variety of purposes. The cost for the plastic used runs about $8-10 per cubic inch. [Strata 2007]

Powder-Binder Printing: Z Corporation

Powder-binder printing works by building up layers of a plaster-like powder that is then sprayed with a liquid binder, or glue, from an ink-jet printer head. In each pass, a new layer of loose powder followed by a pass by the printer head applying the binder. If you imagine each layer of powder as something like a piece of paper, it's virtually the same process as ink-jet printing, except that each layer binds to the next and the powder that isn't sprayed can later be brushed away to leave the constructed part. As the printer builds the object from the bottom to the top, the powder can hold any overhanging parts in place, so no supports are needed. Once the parts are printed, they are removed from the bed of powder and dusted off, and unused powder can be recycled.

Z Corporation, or Z Corp as it's often known, offers printers in the range of approximately $25,000 to $50,000. All models can build excellent parts; the highest price system can build the largest models (10 x 14 x 8 inches) and can add color. Z Corp printers generally build parts more quickly than FDM printers, although it's hard to compare because so many factors are involved. The most commonly used powder results in parts that are attractive but somewhat brittle, although infusing them with cyanoacrylate ("super glue") can make them stronger. Z Corp offers a range of materials with different strengths and properties. The most common powder runs about $5 per cubic inch. [ZCorp 2007]

New technologies: 3D Systems VFlash, Desktop Factory, Fab@Home

Venerable 3D Systems announced that they would bring a new 3D printer to market before the end of 2007. The VFlash printer, manufactured by Canon, is set to be offered at approximately $10,000, setting a new mark for low-cost 3D printing. While the details of the operation of this printer were not available at the time this paper was prepared, it's known to build layers with a light-curable film. Unlike other printers, the VFlash will build its parts from the top down. Anticipated costs for materials are in the $10 per cubic inch range. [3DSystems 2007]

Desktop Factory is a startup launched by the Idealab incubator in Pasadena, California. Desktop Factory has announced that their initial system, the 125ci, would be sold for $5000 per unit, but no firm time for availability has been quoted. At least one beta system is undergoing field testing at this time. The Desktop Factory system deposits layers of aluminum-filled nylon powder which are bound together using the heat of a halogen lamp and a roller. Because of the metallic content of the powder, the Desktop Factory parts will probably be the hardest and most durable available. Desktop Factory views education, at the college and secondary level, as key markets. They intend to offer a very low cost for build materials, perhaps in the $1-$2 range. Because of the appeal of an inexpensive and highly compact 3D printer, they have received considerable publicity, including an article in the New York Times. [Desktop 2007a, Desktop 2007b, NYTimes 2007].

Fab@home is an experimental project based at Cornell University. They have developed open-source plans and software to support a kit-based printer that can be assembled for about $2300 in parts. The Fab@home model 1 uses a syringe to deposit material in a manner similar to FDM. The inexpensive syringe makes it easy to experiment with different materials from glues to cake frosting. According to their web page, about a dozen machines have been constructed by late 2007. By offering a low-cost, open source machine, the Fab@home has the potential to spawn new innovation and creative uses of 3D printing technology. [Fab 2007]

Conclusion

While rapid prototyping machines have in the past been large, expensive "equipment", a new generation of 3D printers is poised to become inexpensive and commonplace peripherals. As these new systems become ubiquitous in our institutions, they have the potential to create some implementation challenges. However, they also have the potential to have a tremendous positive impact for our students and faculty. Technology management and staff are well-advised to start to become familiar with 3D printing so that they can be leaders in incorporating this exciting new technology into their institutions.

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