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3-D PRINTERS FOR LIBRARIES

2017 EDITION

Jason Griffey

Library Technology Reports
Expert Guides to Library Systems and Services

JULY 2017
Vol. 53 / No. 5
ISSN 0024-2586

Library Technology
REPORTS
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3-D Printers for Libraries, 2017 Edition

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Volume 53, Number 5
3-D Printers for Libraries, 2017 Edition
ISBN: 978-0-8389-5988-6

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Library Technology Reports (ISSN 0024-2586) is published eight times a year (January, March, April, June, July, September, October, and December) by American Library Association, 50 E. Huron St., Chicago, IL 60611. It is managed by ALA TechSource, a unit of the publishing department of ALA. Periodical postage paid at Chicago, Illinois, and at additional mailing offices. POSTMASTER: Send address changes to Library Technology Reports, 50 E. Huron St., Chicago, IL 60611.

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Abstract

This issue of *Library Technology Reports* (vol. 53, no. 5), "3-D Printers for Libraries, 2017 Edition," explains both the practicalities of 3-D printing and also its promise and potential. A better understanding of the basics and the theory behind the hardware is a great grounding for determining the best ways to integrate 3-D printers into your library services. Author Jason Griffey concentrates on the areas where much has changed in the last several years, starting with the variety of materials that are now available for printing. Then he discusses the types of 3-D printing software, including a relatively new set of tools that are designed to make 3-D printing much easier from a management standpoint. Next, he looks at the brands of printers that are available and how best to consider them when making purchasing decisions. And finally, he presents recommendations for library 3-D printing setups. This report will help you better understand the technology involved and will also provide you with a set of recommendations and best practices that will enable you to put together the very best 3-D printing setup for your library, your librarians, and your community.

This report is an updated version of the 2014 issue of *Library Technology Reports* 50, no. 5 "3-D Printers for Libraries."

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Chapter 1

Introduction

When I set out to write an issue of *Library Technology Reports* on 3-D printing in libraries back in 2013, it was still a fairly new service for libraries to offer. It wasn't a new technology, exactly, as I'd been writing about it since 2007 or so, and it was gaining ground quickly in consumer news outlets and other media. The biggest change for 3-D printing in 2012–2013 was that the price for the technology was suddenly affordable for libraries, and the ease of use hit a level where it was something that most libraries could put in front of their patrons. Thanks to early innovators like MakerBot and the RepRap community, the technology progressed at an unbelievable pace in the 2011–2014 time frame, and since then 3-D printing has become nearly a standard offering for libraries in most metropolitan areas, and even in more rural locations the likelihood of seeing a 3-D printer is very high. Amanda Goodman has put together what I believe is the most comprehensive map of 3-D printers in libraries anywhere; it can be found at the link in the gray box. As you can see on the map, this is a technology service that has spread very rapidly in just the last five years.

Amanda L. Goodman, Map of 3D Printers in Libraries
www.amandagoodman.com/3D

The goal of the first version of this report was to educate librarians about the basics of 3-D printing—how it works and what the different options are—and provide a beginning understanding of the technology. This report will be slightly different in that there is a great deal more general knowledge about 3-D printing at this point. I will still begin with an overview of the technology because a better understanding of the basics and the theory behind the hardware is a great grounding for determining the best ways to integrate 3-D printing into your services at the library. I'll then concentrate on the areas where much has changed in the last several years, including the variety of materials that are now available for printing, and look at the brands of printers that are available and how best to consider them when making purchasing decisions. Finally, I will look at a relatively new set of tools that are designed to make 3-D printing much easier from a management standpoint and outline the types of printer management software that are now available for use by organizations.

My goal for this issue of *Library Technology Reports* is to explain both the practicalities of 3-D printing and also its promise and potential. When you finish reading this report, I hope that you will not only better understand the technology involved and the variety of options for service to your patrons but will also have a set of recommendations and best practices that will help you put together the very best 3-D printing setup for your library, your librarians, and your community.

What Is 3-D Printing?

The simplest way to imagine a 3-D printer is that it's a machine that makes bigger things out of smaller things. In some cases, the "smaller things" are a powder; in others, they are melted plastic; and in yet others, they are an ultraviolet light-sensitive resin, but in every case it's just a matter of large things being made from smaller substrates. A 3-D printer is a simple sort of robot that understands how to manipulate the raw material it's working with in three dimensions, rather than just two as an ink-jet or laser printer does. This type of manufacturing is also called *additive* manufacturing, as opposed to more traditional subtractive manufacturing, where material is removed from a larger sample to create custom shapes in a process like milling, lathing, or CNC (computing numerical control) machines.

Imagine that you take an ink-jet printer and, instead of printing with ink, it extrudes hot plastic that cools quickly. Think of it like a hot glue gun, where the plastic is solid, then gets heated to a liquid state, and then cools again into a solid. If it printed this plastic onto a piece of paper, you'd end up with a slightly raised design being "drawn" on the paper by the printhead moving back and forth across the paper (the *x* dimension) and the paper being moved through the print area (the *y* dimension). Those of us old enough to remember the days when color printing was very expensive might have memories of hot-wax printers that did basically this.

With a 3-D printer, you add the last of the spatial dimensions, height, by moving the printhead and printing substrate (usually called the build platform in this case) apart from each other. In our ink-jet analogy, imagine that you put the printhead on an elevator that could move it closer and farther away from the paper. If you do that while the printhead is putting down plastic, you can just keep moving them farther and farther apart, layer after layer, in the *z* dimension. Over time, you end up with an object made of very thin layers of this plastic. That's what most 3-D printing is like.

This is the basis for almost all of the 3-D printing that you have seen in media over the last few years and almost all 3-D printing that libraries have been involved with. As we'll learn in the next section, this isn't the only type of 3-D printing—it's just the most affordable.

What Are the Types of 3-D Printing?

In the last section, I described the most common type of 3-D printing as a sort of robotic hot glue gun. This process, only one of multiple kinds of 3-D printing that are available, is usually referred to as *fused deposition modeling* (FDM) printing. In this section, we'll take a look at not only FDM printing but also other technologies for 3-D printing such as selective laser sintering, stereolithography, laminated object manufacturing, and electron beam melting. Most of these printer types are not ideal for library use due to either price, difficulty and specialization of uses, or the fact that they don't fit the service model that libraries are accustomed to.

I'll start with the printing technology most central to libraries at the current time, fused deposition modeling. After discussing that technology, we will briefly look at the wide variety of filaments available now for these printers. The material science efforts to improve the plastics available for printing have been steadily churning out new and interesting filaments with wide-ranging properties. We'll look at those and how each of them might fit into the services offered by a library.

Fused Deposition Modeling Printing

Fused deposition modeling (FDM) is what most people understand to be 3-D printing, as this technology is by far the most common and in many ways the simplest of the possibilities for 3-D printing. FDM typically uses plastic filament that comes in rolls, usually either 1.75 mm in diameter or 3 mm (sometimes listed as 2.85 mm). This filament can be made of nearly any plastic that fits the right melting/glass temperature curve, typically between 150 and 280 degrees C or so. The most common plastic early in the development of 3-D desktop printers was ABS, but it has slowly fallen out of favor due to thermal instability (ABS needs stable air temperature during printing to avoid too-quick cooling, which can cause layer separation). In the next chapter, we'll cover a wide range of new and exciting types of filaments, all of which have significant advantages over ABS.

The most common arrangement for an FDM printer is called a Cartesian print engine because it uses basic Cartesian coordinates (*x*, *y*, *z*) to create the printed objects. There are multiple types of printers even within this general category, although two are more common than others: the MakerBot style, which relies on a fixed plane *x* and *y* printhead and moveable *z* print bed, and the so-called "RepRap" style, which relies on a fixed plane *x* axis while the *y* axis is controlled by moving the print bed itself, and the *z* axis is accomplished by moving the entire printhead system vertically upwards (see figure 1.1).

One other significantly different geometry for a FDM printer is called a Delta printer (figure 1.2). In this instance, the printhead is suspended from three arms that are controlled along vertical supports while the print bed is completely stationary. This arrangement allows the printhead to "float" above the print bed and be located at any physical point in three dimensions simply by altering the relation of each of the three arms to the others. This is the same sort of control geometry at work in the flying cameras used in NFL games, applied to a robot.

The final geometry type of FDM printer is a multi-axis arm. These are very rare and are not (yet) consumer-level, although they are used in laboratory settings. In this type of printer, the printhead is attached to the end of a multi-axis robotic arm and can extrude

Figure 1.1
Left: RepRap style 3-D printer Fabbster from Sintermask (photo by Creative Tools—http://flic.kr/p/dnDyEB; CC BY 2.0, https://creativecommons.org/licenses/by/2.0). Right: MakerBot style 3-D printer Ultimaker (photo by Mirko Tobias Schäfer—http://flic.kr/p/fcuDBM; CC BY 2.0, https://creativecommons.org/licenses/by/2.0).

plastic onto a print bed, or onto pre-existing parts, or really anywhere, limited only by the reach of the arm (figure 1.3). Think about a robotic arm that assembles circuit boards or allows for remote surgery, except with an FDM extruder for a hand. These are fairly new and ridiculously mechanically complicated compared to the relative simplicity of the Cartesian or even Delta printers. However, over time, it is possible that these will become far more available and affordable. If so, many of the geometric limitations of traditional FDM could be mitigated.

Regardless of the control geometry used, the method of printing is the same for all types of FDM printers. The printhead for all is a metal tube with a heating element and thermistor to control the temperature. The plastic substrate is melted by the high heat of the printhead, and pressure is applied by forcing more plastic in, causing some of the liquid plastic to extrude through a small nozzle that ranges from .2 mm to 1.2 mm in size.

A print from an FDM printer begins with a single layer of plastic applied very thinly to the print bed, the nozzle moving across the print bed and depositing said plastic in the shape of the object it's creating. This initial layer is the base layer of the object, and the second layer will be deposited directly on top of the first and will fuse with the base layer due to the properties of the plastic involved. Once the second layer is completed, the third, fourth, and so on will be done, building the object over time along the *z* axis. You can think of layer height as the equivalent of the DPI of a printed page. It's the resolution of the object in the vertical dimension, and the smaller the layer height, the smoother the final product will appear. It will also take significantly longer to print since as you lower the layer height, you're adding layers to the overall build.

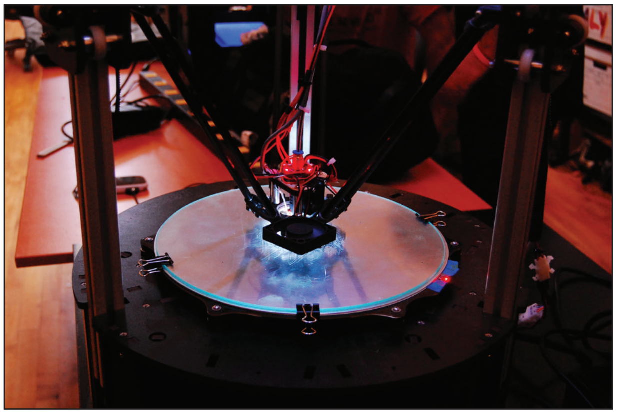

Figure 1.2
Rostock Max Delta 3-D printer (photo by HeatSync Labs—http://flic.kr/p/fzuDbJ; CC BY-SA 2.0, https://creativecommons.org/licenses/by-sa/2.0).

For example, imagine you're printing a 5-cm-tall cube. If you print that cube at what would be considered a fairly rough layer height of .3 mm, you'll end up printing a total of 167 layers. If you print that same cube at a fine resolution (for most printers around .1 mm), then you'd end up printing 500 layers, tripling the number of overall layers and the time necessary to print the object.

Because FDM printers rely on building objects vertically in the open air, they have issues with specific geometries of objects. Imagine an object being printed slowly from the bottom up; if the object has a significant overhang or free-hanging part like a wide doorway or something like a stalactite, it won't be printable without supports on an FDM printer. There has to be something upon which the plastic is deposited; otherwise the print will fail (figure 1.4).

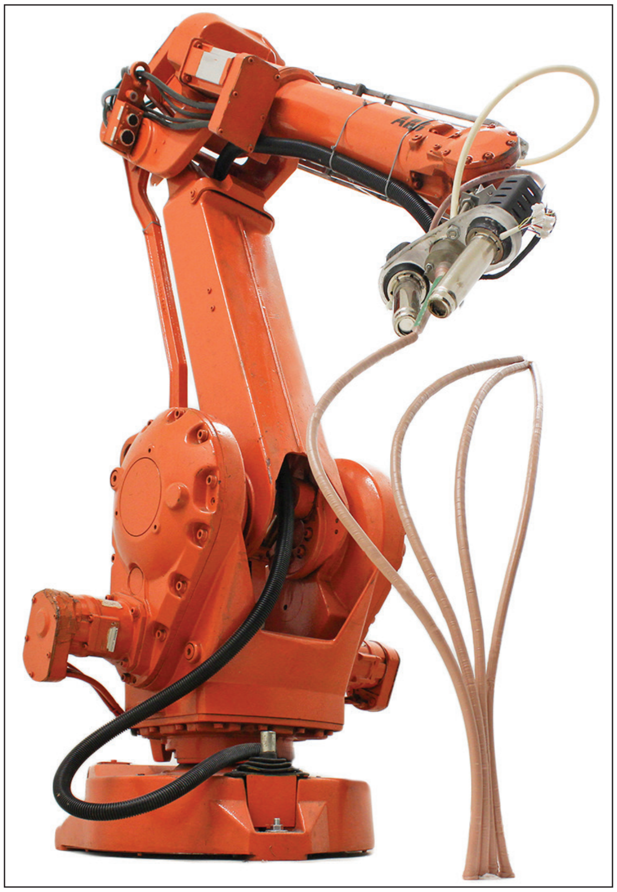

Figure 1.3
Mataerial multi-axis 3-D printer (source: Mataerial home page, accessed April 25, 2017, www.mataerial.com).

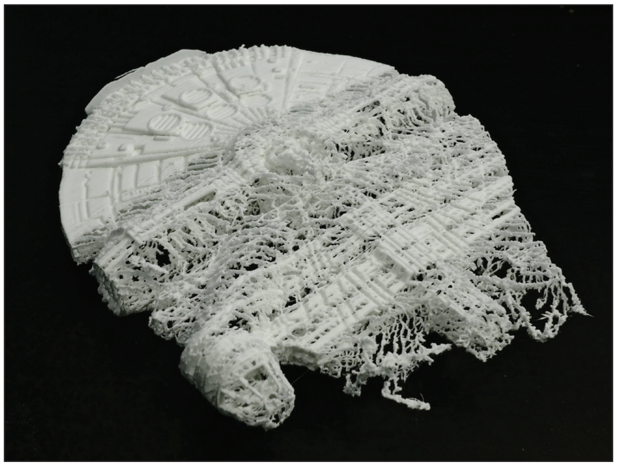

Figure 1.4
Fillenium Malcon fail (photo by flughafen—http://flic.kr/p/DwaefJ; CC BY 2.0, https://creativecommons.org/licenses/by/2.0).

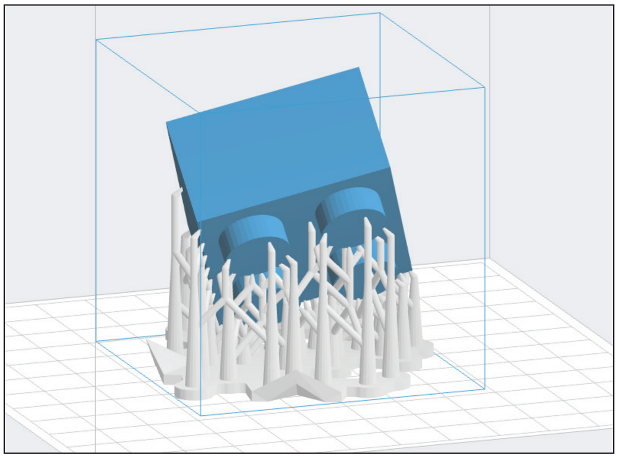

Figure 1.5
Support structures for a Lego block (Source: Wikimedia Commons, accessed April 25, 2017, https://upload.wikimedia.org/wikipedia/commons/1/1e/Supports_in_3D_printing.png).

All FDM printer software has the built-in ability to include supports for printing when issues like this arise. Printing an object with supports means that the software builds in vertical towers (figure 1.5) whose only purpose is to give the object a structure upon which to print. The best case for a support structure is that it would be easily removable from the rest of the model, either by just peeling them apart or, in a slightly more advanced process, by printing supports in a type of plastic that is soluble in a solvent while printing the object itself in a plastic that is insoluble. The most popular of these (discussed in more detail in the next chapter) is high-impact polystyrene, or HIPS, which allows a printer with dual extruders to print support structures that can be dissolved off the actual print.

As with any sort of specialty product, there's a vocabulary that has built up around 3-D printing, and if you're new to that vocabulary, some of the specific terms are inscrutable without research. One example would be the two types of extruder setups found on FDM printers. The extruder is the part of the FDM printer that forces the plastic filament into the hot-end and through the nozzle onto the build plate. One is simply called a direct extruder, while the other is known as a Bowden extruder. On a direct extruder FDM printer, a motor is on the moving print assembly that includes the hot-end and the nozzle, and the motor pulls filament off the spool and drives it directly into the hot-end. The majority of FDM printers have a direct drive extruder. The Bowden extruder removes the motor assembly from the hot-end and nozzle and takes it off the moving printhead altogether. In a Bowden setup, the motor pushes the filament from the spool through a tube connected to the hot-end and nozzle. The advantage to the Bowden is that it significantly reduces the weight of the moving print assembly, which means that the print assembly can move more quickly and can change directions without the problem of momentum inherent in moving a heavy object precisely and quickly, known in 3-D printing as jitter. The disadvantage is that it is, in some sense, pushing a rope, and the more flexible the filament, the harder time the Bowden setup will have pushing it into the print assembly.

A few other FDM-specific terms that would be good to know would be (and some of these I've already used without explaining, forgive me, dear reader): hot-end, build plate, nozzle, and spool. The hot-end of an FDM printer is the metal piece that has the heating element in it and melts the filament. This is normally some form of nonreactive metal, either aluminum, brass, or stainless steel. The nozzle is the very small diameter metal end (.2–.5 mm) through which the melted plastic is forced under pressure on its way to the build plate. There is a relationship between the nozzle diameter and the possible layer height of the output from the printer. Because you are extruding tubes of melted plastic and they need to be pressed together in order to fuse, the layer height can't be any larger than the diameter of the nozzle. If it were, you would be extruding into thin air, without the new layer pressing into the old layer. To help you visualize this, think of it this way: if the width of your extruded plastic is .3 mm and you attempt to print at a .4 mm layer height, there's .1 mm between the plastic and the layer below it—not good. In practice, a good rule of thumb is that the maximum layer height is somewhere between 75 and 80 percent of the nozzle diameter. So for a .4 mm diameter nozzle, your maximum layer height would be around .3 mm. Generally speaking, the goal is to have lower and lower print heights, as that makes for a smoother and smoother final product. But for rough prints or demos, having a higher maximum layer height can speed up prints tremendously.

The last couple of FDM specific pieces of terminology are build plate and spool. Spool is easy, as it's the way that filament is generally purchased and used. A typical purchase of ABS or PLA would be a kilogram (2.2 pounds) of plastic, wrapped onto a plastic or cardboard spool that hangs on the printer and plays out filament as needed. In an FDM printer, the build plate is the surface upon which the plastic is extruded. The specifics vary widely, but fall into a few basic categories, the primary of which is heated or nonheated. A heated build plate adds cost to the printer, but is absolutely necessary for printing certain types of filament (ABS, nylon, and more).

Another aspect of the build plate is what it's made of and whether you print directly onto the plate, onto some tape or other covering, or onto a glue or other adhesive. Heated build plates are usually made of either aluminum or tempered glass, although occasionally stainless steel shows up. Unheated build plates can be composed of the same things, as well as acrylic. The crucial thing with build plate construction is that you want something that will not warp or deform over time, since if the plate itself isn't flat, it's impossible to level it appropriately to the printheads. Glass is a very popular build plate material for this reason, although many FDM printers ship with aluminum plates that are then covered with a replaceable printing surface of some kind, most commonly PET tape or Kapton tape for a heated bed, or painter's tape for a nonheated bed.

The price points for FDM printers are typically determined by size, more specifically print volume or the size of the print bed, and a variety of upgrades that make specific kinds of printing or printing with specific plastics more easily done. Print bed sizes range from very small (no more than 3 inches by 3 inches or so) to massive (over 12 inches by 12 inches). The print volume determines the maximum size of a single object that you can print or, conversely, the number of smaller objects that you could print at the same time. Printing larger objects is also more difficult because as you print larger things, there's more opportunity for a small error to creep into the print due to any number of common 3-D printer issues, such as a nonlevel build plate or thermal layer separation from ABS filament.

Challenges with Fused Deposition Modeling

In the first edition of this report, the largest challenge that I identified for reliable 3-D printing was the calibration of the printer itself—specifically, the leveling of the print bed in relation to the printhead. In early FDM 3-D printers, and still on many models, this leveling was manual. Accomplished by hand-turning screws that moved the corners of the print bed, all the while measuring the gap between the print bed and the extruder nozzle with a piece of cardstock, it was (and sometimes is) a ritualistic but necessary component of using 3-D printers.

However, many FDM printers, including the specific brands and models that I recommend that libraries purchase, have some form of autoleveling in place. This is a process that varies slightly in different printers, but it boils down to the printhead having the capability of measuring its offset to the print bed and either adjusting that offset automagically in software (as the LulzBot printers do) or walking you through an automated set of resources to make the calibration process easier. One of the main reasons that I continue to recommend LulzBot printers is that I cannot overemphasize how liberating it is to have and use a printer that doesn't require manual leveling. It saves, without exaggeration, fifteen to twenty minutes a day at least, and that time adds up for a busy library.

If your library is unlucky enough to still have a manual-calibration FDM printer, this is likely the source of much of your frustration with the device.

The other major source of frustration comes from issues relating to the filament used. Sometimes the filament being used is wrong for the physical environment of the printer: for instance, ABS or other thermally sensitive plastic used in an environment without careful temperature controls. The final set of problems that I have seen crop up in library FDM printing is the improper storage of filament. Certain kinds of filament are humidity-sensitive, and some plastic is highly hydrophilic. If the filament absorbs too much water from the air, its properties when heated can change, and this can cause issues with the extruder due to the water converting to steam at the hot-end. Filament should be stored in a closed container, such as a large plastic tub with lid, and ideally with a few desiccant packs included in the container. That will ensure that it doesn't absorb too much water and should remain stable for printing for a very long time.

Stereolithography

While FDM printing is by far the most common inexpensive method of 3-D printing, we are starting to see stereolithography (SLA) printing move down market into the affordable-for-libraries zone. I'm aware of a couple of libraries that have already purchased stereolithography printers, so it is starting to trickle into our midst. What is stereolithography 3-D printing? It's a method of 3-D printing that involves a light-sensitive resin and lasers. The way it works is that a liquid resin is contained in the body of the printer with a build plate that moves up and down inside the resin. The resin solidifies when exposed to a specific wavelength of light, usually in the UV spectrum, and the printer has a laser or lasers that are tuned to that specific wavelength. The build plate starts near the top of the resin, and the lasers sweep across, solidifying the resin in the appropriate areas. The build plate then lowers, and the lasers repeat their sweep, building layer after layer, one after the other as the object is built. You can also have this process occur upside down, as in the Formlabs Form 1 printer, where the build plate is actually above the resin, and as layers are added, it pulls the completed layer out of the resin.

This type of printing has several advantages over FDM printing. The first is that because the print is always encased in liquid resin as it prints, it is much more forgiving as to geometry of design. Not completely, as there still has to be some connection to the base layer (you couldn't print a "floating" horizontal piece, for instance). But in general, the resin provides substantially more support than is possible with FDM printers, allowing you to print a greater variety of geometries. The other major advantage is that the detail level is limited by the crystallization of the liquid and the size of the lasers, which means that you can have very, very fine details in an SLA print. It's possible to achieve .025 mm (25 microns) layer heights with SLA prints.

Stereolithography printing is limited in some ways as well. The first is that the resin is available only in a very limited number of colors, generally a clear or translucent material and white. When compared to the rainbow of colors available for FDM printing with ABS or PLA, it feels limiting. The second, and far more worrisome, limitation is that most vendors of this type of printer manufacture their own resin, and it's possible to tune the wavelength of the lasers involved to the specific resin they sell, thus making it very difficult for anyone to compete with them on consumables for the printer. This would be the equivalent of buying a printer from HP and having to then buy paper and toner from HP as well in order to use the printer.

Small SLA printers in the $2,500 to $3,500 range are just beginning to hit the market. Though consumable for printing, the photosensitive resin is more expensive than filament for FDM printing. The most popular of consumer-grade SLA printers, the Formlabs Form 1, has resin that sells for $149 per liter.

Selective Laser Sintering

Simultaneously, the most flexible and the most expensive type of 3-D printing commonly used, selective laser sintering (SLS) printing, is similar to stereolithography in that it uses lasers to solidify a loose substrate. The difference is that for SLS the printing substrate is a powder and you use high-energy lasers rather than UV ones. The high-energy lasers selectively fuse sections of a powder together. A new layer of powder is deposited on top of the sintered layer as the entire print bed drops, and the lasers do another pass, fusing the single-layer of powder to the already solid layer below. Thus prints are completed layer by layer, exactly as in the other printing technologies that we covered, except the end product is a solid object that's been drawn by lasers, encased in all of the powder that wasn't fused.

This method provides total support for the print in question, so nearly any imaginable geometry can be printed using SLS printing. It is also possible to use any material for SLS that is capable of being powdered and fused with heat, including most of the previously mentioned thermoplastics as well as steel, aluminum, titanium, and other metals and alloys. Prints produced in this way are very nearly as strong as solid-cast parts, which means that it's possible to 3-D print mechanical parts that are directly usable in engineering projects via SLS printing.

Layer height and resolution in SLS printing are completely determined by the resolution of the powder being fused, but they are typically on par with SLA printing, averaging around .1 mm layer height.

Another similar technology is electron beam melting (EBM), which uses high-energy electron beams to melt powdered metals in order to produce 3-D objects. The use of electron beams allows for even higher precision than lasers, allowing for down to .05 mm layer heights, which is nearly unheard of by any other method.

Laminated Object Manufacturing

The last specific type of 3-D printing that I'd like to describe is, in my opinion, particularly clever. Laminated object manufacturing takes thin materials like paper or plastic sheets, cuts them to a specific shape, and then uses adhesive to glue one layer to the next. The best known of these types of printers is manufactured by a company called Mcor Technologies. Its printer uses normal, ordinary copy paper as its substrate, cutting one sheet at a time into the appropriate shape for the given layer, and then using paper glue to laminate the individual layers together. The high-end model of the Mcor printer includes a full-color ink-jet printhead inside to allow full-color 3-D prints to be created from very inexpensive raw materials—literally paper, ink, and glue.

Other 3-D Printing Types

There are numerous other 3-D printing technologies in existence, especially those that are patented and limited to a single company. For example, 3D Systems uses a 3-D printing methodology that it calls ColorJet Printing (CJP), which uses two different materials that are combined using a sort of high-end ink-jet printer in order to create the solid end product. This patented process allows 3D Systems to print in materials like food-grade ceramic. 3D Systems also makes a 3-D printer that is capable of printing in sugar, called the ChefJet, and the high-end model, the ChefJet Pro, can print edible 3-D models in full color.

Chapter 2

Types of Filaments for FDM Printing

Since FDM printing is the most common type of 3-D printing for libraries to have, this section will do a deep dive on the materials available for libraries to use. The last few years have seen a blossoming of material types available, both in terms of ease of use and of specialty materials that offer unique properties.

The substrate for FDM printers is almost exclusively some form of thermoplastic that is delivered in an extruded wire-like form on a spool and is usually called *filament* in the generic. The two common diameters for use in FDM printing are 1.75 mm and 3 mm, and a specific diameter is called for by the printhead being used for the printer in question. A printer that uses 1.75 mm diameter filament won't be able to use 3 mm without the hardware being retrofitted for the difference, and a 3 mm printer won't be able to use 1.75 mm filament without at least the software involved being adjusted and perhaps the hardware as well. These restrictions on changing from one size to the other in a given printer are a combination of many possible issues: the path the filament follows through the extruder, the size of the hot-end and its ability to generate heat quickly enough to melt the filament appropriately, and the amount of extrusion programmed into the code that describes a given print. Any or all of these may be a problem if you attempt to move from one filament size to another with your printer.

In general, a library should look at its printers and try to stay within a specific filament size across all of its purchases, thus maximizing the flexibility of its material budget. Early in the 3-D printer movement, 1.75 mm was more popular, but in the current environment, it is a fairly even mix. Both of the 3-D printer companies that I recommend to libraries (LulzBot and Ultimaker, both of which are discussed in chapter 4) use 3 mm filament primarily, so it is a thing to watch for.

As I discuss the different printer types and manufacturers in chapter 4, I'll make a point of talking about what type of filament they are capable of printing because that turns out to be a major limitation for the purchasing decision.

ABS

The original fused deposition printers almost exclusively used ABS (acrylonitrile butadiene styrene) as their substrate for printing. ABS has nearly ideal material properties for rapid prototyping in plastic, as it's a strong, slightly flexible plastic that extrudes cleanly between 220 and 240 degrees C. ABS, the type of plastic used in Lego bricks, is one of the most commonly used industrial and commercial plastics.

ABS requires a heated print bed to ease the thermal shock for FDM printing. Heating the print build plate aids the plastic in both adhering to the plate for stability and in not cooling too quickly, which could lead to thermal deformation, a sort of curling or separation when ABS cools rapidly after being extruded. ABS is sensitive enough in this arena that many people who print ABS learned early that enclosing the printer was a way to increase the stability of prints because it regulated the temperature around the printer. I discovered early in my printing experiments with an early MakerBot printer (Replicator 1) that even a strong breeze blowing in the wrong place (i.e., across the print bed) could wreak havoc with getting a good print out of the printer. Higher-end printers will have an enclosed print area built in, while less expensive ones won't.

One of the advantages of ABS is that it dissolves in acetone. Acetone dissolves ABS completely, but used sparingly it can act as a glue to fuse two ABS printed pieces together permanently. Acetone is also used to make a "glue" to help make the print bed sticky for the initial printed layers. Acetone vapor is heavier than air, and some people have used this property to build acetone vapor baths that act to smooth the edges of layers of an FDM ABS print.

ABS has caught some bad press as the potential effects of off-gassing of the heated plastic and microparticulate effects are studied. As a petroleum-based plastic, ABS does produce a distinctive stink when printing. Fumes have been reported to cause headaches. There are studies that link ABS fumes to olfactory loss, and one study found ABS printing to release high volumes of ultrafine particles that could be dangerous when inhaled. These are preliminary studies. Most haven't been repeated, and the science is still rough on the health effects. But if you need to print with ABS, it may be a good idea to take venting into account.

The good news is that over the last two to three years, huge numbers of new filaments have been developed and have lowered the reason to use ABS at all, especially for libraries. Given the cost/benefit ratio of other filaments, I typically don't recommend that libraries invest in ABS as a printing filament at all these days.

PLA

PLA (polylactic acid) is, at this point, probably the most popular printing substrate for FDM printers. PLA is a bioplastic made from corn, beets, or potatoes. It is compostable in commercial compost facilities (the heat and bacterial action in home composting aren't high enough to break it down). PLA melts at a much lower temperature than ABS (150–160 degrees C) but is typically extruded at a higher temperature, anywhere from 180 to 220 degrees C depending on the PLA itself. Because of its lower melting temperature, it's not suitable for uses that involve high temperatures and direct sunlight. PLA is also very different from ABS in terms of fragility, as PLA is far more crystalline and shatters or cracks more readily than ABS, rather than deforming under pressure.

PLA doesn't require a heated bed for adhesion or thermal curling reasons, which lowers the price of the printers that use it. In addition, it's far more thermally stable during printing than ABS and much less likely to warp or curl due to errant breezes. It is possible to reliably print PLA without needing to enclose your printer, which can be a huge benefit in many circumstances. Drafts and other thermal shifts don't affect PLA printing to any significant degree, which makes for more reliable and stable printing. In public service situations, that reliability is a very big deal.

The other significant advantage is that PLA is far more pleasant when printing than ABS. Because it is a bioplastic, when heated it smells like waffles or syrup and not like an oil spill. It also hasn't been linked to any types of medical issues from being heated, although the study of all these plastics is young when it comes to 3-D printing specifically.

One of the other advantages of PLA is that it's available in dozens and dozens of colors, including both opaque and partially transparent, as well as a couple of glow-in-the-dark colors. It also is available in a flexible form, which can produce prints that are almost rubber-like in consistency.

If you are printing in a library setting, PLA is a great material to work with and is one of the filament types I would recommend as a primary offering for your 3-D printing service. Between the reliability and the ease of working with it, it's a far better choice than ABS for printing in a public space.

Other Filaments

A number of filaments have emerged that have really changed the possibilities of 3-D printing. When I published the first edition of this report, ABS and PLA were really the only recommended filaments for printing, and everything else fell into a general "experimental" category. Now, there are so many different filaments that it will be difficult to even list them all. I'm going to start with what I would call "standard" filament types, those that are excellent for general 3-D printing use, and then follow up with the more specialized or unusual filaments that could be used for specific reasons or projects.

nGen

nGen is a proprietary filament type that is produced by colorFabb, a company dedicated to the creation of new and interesting 3-D filaments. It's made of a type of plastic produced by the Eastman Company (Eastman Amphora 3D Polymer AM3300) that is designed specifically for 3-D printer use. As a result, it combines many of the best characteristics of both PLA and ABS. It is thermally stable and prints at a reasonably high temperature (thus making it stable at higher temperatures than PLA). It's also low-odor and safe for printing in ways that ABS may not be. It is comparable in cost to PLA and is currently the filament type that is recommended by Aleph Objects, the maker of the LulzBot series of printers and my choice for the best 3-D printer company.

If I had to choose only one kind of filament to use for all my 3-D printing, it might be nGen. The only downside to it compared to PLA is that it is not compostable, but it beats PLA in toughness, look, mechanical strength, and almost every other measure. It does require a heated print bed but is still my current go-to filament for 3-D printing.

n-vent

Similarly named, but wholly different from nGen, n-vent is a brand of PETG (polyethylene terephthalate + glycol) that is also marketed by colorFabb as colorFabb_XT filament. It shares many similar properties with nGen and is a fantastic alternative to ABS. It has very limited odor or other safety concerns regarding printing but maintains the flexibility and strength that ABS provides. It is a very strong material, suitable for mechanical pieces, and doesn't require a heated print bed for reliable printing. Both n-vent and nGen are examples of the sort of innovation that physical materials have gone through over the last few years.

HIPS

High-impact polystyrene, or HIPS, is a petroleum-based plastic filament that extrudes at around 235 degrees C and has material properties that make it very similar to ABS. HIPS is very thermally stable and is very light for its strength. One unusual property of HIPS is that it is completely soluble in a liquid hydrocarbon called Limonene. This means that if you have an FDM printer with more than one printhead, you can extrude with a nondissolvable filament type (ABS, PLA) from one extruder and use HIPS as a support material from the other and sit the final printed model in a bath of Limonene. The HIPS will dissolve away, leaving only the ABS behind, thus allowing for nearly impossible geometries to be printed, including moving ball bearings and more.

At one point, HIPS was seen as a good generic filament for printing, but with the rise of materials with better physical characteristics, such as nGen, HIPS has fallen out of favor for anything except dissolvable supports.

Nylon

Multiple types of nylon can be used for 3-D printing, but they all share a few important characteristics. They all are extremely sturdy, really about as tough as 3-D printed parts can be. They have extremely high layer adhesion and very strong mechanical properties, which leads to printed pieces that can easily be used in machinery and other movable installations. They are also very resistant to solvents and very chemically stable.

Nylon as an FDM printing material is more expensive than PLA or ABS and is not as pleasant to print as PLA, nGen, or other filaments. The major reason for using nylon would be for specific material properties (resistance to specific chemicals) or in order to take advantage of its ability to be dyed with fabric dye, a unique characteristic in the 3-D printing world.

T-glase

T-glase is a brand name for a filament composed of polyethylene terephthalate (PETT). Of all 3-D printer filaments, it is the most glasslike. It is very clear—nearly transparent, especially at small sizes or printed with large layer heights. At larger sizes it is still very light-transmissive, if not fully transparent. T-glase prints at around 221 degrees C on a heated bed but is very stable and resistant to curling.

Specialty Filaments

Filament manufacturers have experimented with adding nearly anything you can think of to their plastic substrates at this point, and many of these experiments have led to interesting opportunities for 3-D printing. The filaments in this section would not be ones that I recommend stocking as a part of your "standard" options for patrons, but they might rise to a particular need for a project. As an example, Laywood (a wood-based filament mentioned below) can be sanded and stained, and once that's done, it's nearly indistinguishable from wood itself—useful in a library where you might want something to blend in with the existing wooden shelving or tables.

Laybrick and Laywood

Laybrick and Laywood are printing material for FDM printers and fall squarely in the experimental realm. They are made by a single manufacturer and are both a sort of hybrid filament, with a powdered material being supported inside a resin. In the case of Laywood, fine wood particles are suspended in a thermoplastic resin, and in the case of Laybrick, very finely crushed chalk and other minerals are suspended in the resin.

Both Laybrick and Laywood have the interesting property of variability in appearance depending on the temperature at which they are printed. Laybrick can range from a very smooth, almost ceramic feel to a very rough sandstone, just by increasing the heat of extrusion. For very smooth, you print at a low temperature (165–190 degrees C); going up from there to around 210 degrees C will render the printed part rougher and rougher. For Laywood, the difference is in the appearance of the final product. By increasing the temperature, you get darker and darker wood grain from the output, so you can actually vary the look from light to dark wood (or, if you have a printer that supports variable temperatures during a single print, you can get different colors in a single print by varying the temperature).

One of the risks, however, with both of these is that the filament isn't uniform in construction, which means that it's possible to clog your extruder if the nozzle opening is smaller than the particulate in the filament itself. FDM printers' nozzle openings range from .35 to .5 mm, and on the lower end of that, especially with Laywood (organic particles are harder to ensure in regular sizes than inorganic particulate), you risk clogging a nozzle. I know 3-D printers that have clogged even at a .4 mm nozzle using Laywood, and for printing these sorts of filaments, the larger the nozzle the better.

Polycarbonate

Only recently have material manufacturers managed to formulate a variation of polycarbonate (PC) that is friendly for use in 3-D printers. PC is even tougher than nylon on many fronts, especially when it comes to resistance to impact and heat. PC is also nearly clear, and post-processing can result in very glasslike prints. It is complicated to print with, however, as it suffers from significant shrinkage during cooling. As a result, it prints most successfully in an enclosed and temperature-controlled print bed. It also requires one of the highest printing temperatures of any filament mentioned here, printing at almost 300 degrees C. It is most definitely a specialty filament, and it is difficult to imagine most libraries ever needing to deal with it.

Conductive

There are a variety of filaments marketed as conductive, mostly based on PLA or ABS substrates. These are made by mixing a small amount of conductive material (typically carbon fiber) into the plastic, thus allowing it to carry low-voltage current. For engineering or makerspace projects, this allows for an inventive use of 3-D printing to create lights or sensors without the use of wire, and in the case of a dual-printhead printer with conductive and nonconductive filaments loaded at the same time, to print circuits directly rather than using a breadboard.

Carbon Fiber

The conductive filament discussed above is usually made with carbon fiber granules, but carbon fiber filament is made with larger filaments or chunks of carbon fiber in it, used as a material to increase rigidity of the resulting prints. It is very successful at this, as prints from this filament type are extraordinarily rigid and strong. It is often used to prototype projects that need this rigidity, such as quadcopter frames; nothing else in the 3-D filament world really approaches carbon fiber filament for weight/rigidity ratio. The downside for carbon fiber printing is that the filament is incredibly tough on printheads and nozzles, as the small pieces of carbon fiber are abrasive to the normally soft nozzle. If you plan to print larger quantities of carbon fiber filament, you will need to regularly check and replace the nozzle on your printheads or upgrade the nozzles to a harder metal (from brass to stainless steel, for example).

Metal Fill

Similar to the Laybrick and Laywood filaments mentioned earlier, the metal fill class of filaments can be PLA- or ABS-based, and they have very fine metal particles suspended in the plastic. This metal can be brass, bronze, aluminum, copper, steel, or other metals. There is a high enough metal content in the filament that it is easy to tell this filament from metallic colored ones simply by weight and density. It is significantly heavier than standard filaments and reacts much as a metal would when it comes to weathering, tarnishing, or (if applicable to the metal type) rusting. Aside from those characteristics, however, there is little material difference between standard PLA and ABS, and these are primarily used decoratively, not functionally.

MOLDLAY

A very new addition to the 3-D printing material options, MOLDLAY is designed specifically around the process of lost-wax casting in metal. It is a filament tuned to have very specific temperature reactivity, as it is solid and stable at room temperature; its phase changes, and it can be extruded at around 170 degrees C. However, it melts and liquefies completely at around 270 degrees C. This allows for the printing of positive shapes that will be used to create a negative plaster mold for metal casting, such as jewelry making, functional iron casting, or other situations that use the lost-wax casting method. It would be the rare library where this was a common enough request that it needed to be on your radar, but it might be an interesting material option for some design schools.

Chapter 3

Software

Before we get into the software proper, let me give you a high-level overview of how the process of printing with an FDM printer works. This is a genericized process and will be very similar regardless of which particular printer you have. You start with a digital model in STL format. You've either created it yourself using one of the software packages described below or downloaded it from a website; either way, you have an STL that you'd like to print. You take that file and open it in a plating and slicing program, like MakerWare, Repetier-Host, ReplicatorG, or Pronterface. That program will let you see how the object sits on the build platform and manipulate it to some degree (scale it up or down, rotate it for a better fit). You will then choose a number of different settings for slicing, things like layer height, infill, and extrusion temperature. Once you have your settings selected, you will either print directly from the computer over USB or export the STL file as a G-code file and move it to the printer on an SD card. The STL will be sliced into hundreds of layers, and the 3-D printer will be given instructions on how to build it one layer at a time.

Now that we have an understanding of the physical process by which 3-D printers work, let's look at the other half of the 3-D printing process: the software. There are three different sorts of software we'll discuss in this section: the software that prepares your designed files for printing (slicing and plating software), the actual design software that allows you to create the 3-D object that you wish to print, and software for managing prints.

We'll start with the design software. There are a couple of different file-type standards for 3-D printing, STL and OBJ. OBJ files are typically those used in high-end printing and include things like color information that are superfluous for the sorts of consumer-level printing that libraries are likely to be involved in. For FDM and SLA printing, the needed output file is an STL file. This is the equivalent of needing a .docx file if you want to work in the most recent version of Word or a PDF file for cross-platform document consumption. The STL file is a very simple description, in either ASCII or binary, of the external shell of a 3-D object in terms of triangles. Nearly every 3-D modeling software that you might use will export to STL—it is that common a file format in 3-D design.

One of the things that has really helped the 3-D printing business take off is the availability of freely sharable STL models of just about anything you can think up. The most popular online library of 3-D models is Thingiverse, a freely available resource that is owned by MakerBot Industries. Thingiverse allows anyone who has created a 3-D model to upload it to the website and make it available for anyone else to download. It's open-access 3-D objects, in effect. Thingiverse is the perfect first stop for anyone who has a 3-D printer, as it will give you hundreds of things to print, from toys to tools. The downloadable files have easy-to-follow instructions for printing if there is anything tricky about the print and clearly labeled intellectual property rights that make it easy to understand what you can do with the design itself.

Thingiverse
www.thingiverse.com

As libraries start creating and sharing more of their own objects, Thingiverse would be the logical place to store them, especially for findability by the

3-D community. I'm hopeful that we'll be able to find shelf brackets and more that are printable and shareable over time.

I'm going to organize this recommendation area for 3-D design software into beginner, intermediate, and expert levels. There are far more options for design software than I can cover here, but this section is intended to give you a solid starting point.

Beginner 3-D Design Software

My favorite piece of software for the beginner in 3-D design is a website called Tinkercad. Tinkercad is a freely available web application that allows the creation of 3-D models by using simple shapes to build up more complicated ones. It requires the creation of an account, but you can get a free account (at least at the current time) that gives you unlimited models online. The only real limitation is that for the free account, your creations must all have a Creative Commons Attribution-Share Alike 3.0 license. Paid accounts get the ability to choose among all of the available Creative Commons licenses as well as the ability to control commercial distribution of their models.

Tinkercad
http://tinkercad.com

Since Tinkercad is entirely browser based and runs on any modern web browser, it's trivial to run on nearly any computer. It has a well-done introductory tutorial for beginners and works by building with simple basic shapes (cube, sphere, pyramid), allowing people who are new to 3-D modeling to start very slowly but still gain an understanding of basic concepts. It also clearly labels the size of objects for output and allows for either solids or holes of any arbitrary shape.

Tinkercad also allows the importing of other STL files, which means that it's possible to download an STL from Thingiverse, import it into Tinkercad, and alter or modify it, although not in the robust way that you could in full 3-D modeling software. For first steps towards creativity in the 3-D realm, it's a fantastic tool.

Intermediate 3-D Design Software

A step up from Tinkercad is SketchUp, a piece of software that was formerly owned by Google but sold off in 2012 to Trimble Navigation. There are two versions of SketchUp available, SketchUp Make and SketchUp Pro. SketchUp Make is freely available for noncommercial use and has every capability that I can imagine a library or patron needing, while SketchUp Pro is really designed for professional architects and others who need very professional level controls and output.

SketchUp
https://www.sketchup.com

SketchUp is ostensibly designed for architectural renderings—building interiors and exteriors, landscape design, that sort of thing. But since, like Tinkercad, it deals in just a few basic shapes and controls, it's very flexible with what it can be used to design. As a bonus, the SketchUp website has dozens of learning resources that you can use to both learn and help other people learn the tool.

SketchUp doesn't natively have the ability to export to STL for 3-D printing, but there is an easily installed plugin that gives it the ability to export or import any STL file. This can come in particularly handy if you are interested in printing buildings, as SketchUp is the primary tool used for creation of buildings for Google Earth and Google Maps. SketchUp maintains a 3-D warehouse of buildings and objects that can be trivially opened and printed, including pretty much every famous building or sculpture in the world. Want a copy of the Taj Mahal on your desk? Not a problem with SketchUp and a 3-D printer. Ditto for the Empire State Building, the Arc de Triomphe, or the Tennessee Aquarium. All of those are available and already modeled for your use.

Advanced 3-D Design Software

Another one of the free tools that I want to mention is Blender. Blender is an open-source 3-D computer graphics program that is used not only for basic 3-D model creation but also for full animation and movie making. In the software that I've mentioned, if Tinkercad is a moped and SketchUp is a motorcycle, Blender is a Saturn V rocket. It is indescribably more complex than either of the other tools to such a degree that I would really recommend it only for people who have previous experience with professional-level 3-D tools.

Blender
www.blender.org

With that caveat, it is a fully professional-level tool that is capable of creating completely realized 3-D photorealistic models. And it's free. This combination means that there's little reason not to at least play with it or have it available if a patron wants to use it. It is worth considering whether or not you will be able to offer assistance to your patrons using Blender because, for most libraries, the answer would be no. This is, I think, not a bad thing; just be aware of the complexity of the program.

The last of the free tools I'd like to suggest taking a look at is OpenSCAD, an open-source CAD editor. It is also a professional tool, but where Blender's strength is in the artistic and creative, OpenSCAD's strength is in the mechanical and engineering aspects of 3-D modeling. If you want to model a turbine impeller or a structural support, OpenSCAD is likely your tool. Much like Blender, however, it is definitively a professional tool and requires serious research and effort to get into.

OpenSCAD
www.openscad.org

Most of the commercial tools for 3-D model creation are tied heavily to specific professions, and it's likely that if your library needs them, you'll already know it because of local demand. Academic libraries specifically may need to pay close attention to the areas they are serving, as classes that use AutoCAD (for architecture, engineering, and construction) are very unlikely to also teach Maya (for 3-D animation), but either may be very important to your patrons.

Host Software

What is usually called host software is the software that you use to interface with the 3-D printer directly, whether it's in preparing STL files for printing or actually creating the output file that the printer understands. This section is going to focus on the software needed for FDM printing, as that's the most likely to be of use in a library (and once you get into SLS and other types, it's more likely that the software and process are proprietary).

Much as a desktop printer doesn't speak Microsoft Word, even if that is the most common file type that you print, 3-D printers don't actually print STL files. An STL is a mathematical representation of a shape, while the 3-D printer itself needs instructions: how much filament to extrude, where and how fast to move the nozzle, how far and when to lower the build platform, how hot the extruder should be. The actual mechanical movements are encoded in a separate file, and the file type depends on the printer in question. Most FDM printers use an open file type called a G-code file that is an ASCII representation of all of the values needed to create the object. G-code is very handy in that, since it's just a text file, you can manually alter known values in order to change the way the print is done. If you want to lower the extrusion temperature, there is no need to re-encode the file; you can just change the value once you know where it is. G-code is also open, which means there are multiple programs that can create it.

The process of moving from STL file to G-code for 3-D printing is called slicing because you are in effect taking the 3-D object and slicing it into thin layers that the printer will reproduce. Some slicing software has a ton of control, letting you plate the models. Plating means placing them on a virtual representation of the build plate of the printer in question, allowing for printing of multiple parts simultaneously by plating more than one STL at once. Other slicing software is more bare bones, allowing you to just make choices to printer settings during the print process.

Cura

My favorite slicing and plating software is called Cura. Cura is an open-source solution for controlling any 3-D printer that uses standard G-code, but more importantly, it's the primary software used by both of my recommended 3-D printer manufacturers (LulzBot and Ultimaker). There are two different "flavors" of Cura, one maintained by each of the two companies, and each company also maintains a full complement of definitions for each of its printers as well as for all of its supported filament types.

Cura, LulzBot edition
https://www.lulzbot.com/cura

Cura, Ultimaker edition
https://ultimaker.com/en/products/cura-software

This software allows for both a rich and a simple printing experience for beginners, who can simply select from drop-down menus to specify what sort of filament they are using in which printer and have all of the myriad of settings for that combination set appropriately. This process almost guarantees successful prints, as the settings have been battle-tested by the companies in all sorts of situations. Expert users who want more control over speed, temperatures, or the flow rate of the filament can easily and quickly switch to expert mode and directly alter the settings they care about.

Cura also has fully featured plating capabilities. You are able to plate single or multiple STL files up to the size limitations of the printer in question. It also allows for manipulation of the files after import in the form of scaling or resizing, rotating, or mirroring individual STL files. This allows for very precise and efficient use of the printing area, and these arrangements can be saved and retrieved for reprinting quickly and easily.

Cura has well-realized visualization features as well, and they can quickly identify issues with a print that might not be seen in other ways. The standard "solid" view can be switched to an "x-ray" view of the model, which allows you to peer inside the STL and see areas that might be problematic in a variety of ways (overhang, gaps, intersections). Cura will even highlight areas of difficulty in red so that you can quickly see what might cause your print to fail. My favorite view to find problems is the "layer" view, which shows you each printable layer and the path that the printhead will take during printing. Especially when considering the first few important layers, this view sometimes shows you the reason your model is troublesome before you waste filament on a failed print. (In my case, it's almost always that somehow the STL file isn't level on the print bed.)

Cura is usable by any 3-D printer that understands G-code, not only models from Ultimaker and LulzBot. If you have any printer that uses open-source software, you can probably give Cura a try. You may need to dial in the settings yourself and create your own definitions, but those are fairly straightforward for the amount of power and ease of use that Cura gives you.

Slic3r

Another popular slicing engine is called, appropriately enough, Slic3r. Slic3r is an open-source project that is usable by itself but is probably more commonly used as a back-end slicing software for more popular packages that include plating and other options. These would include MatterControl, Pronterface, ReplicatorG, and Repetier-Host, the most popular management software for 3-D printers. I'll discuss management software further in the next section. Slic3r does allow for rough plating of objects, but its strength is in the detail given to the slicing process.

Slic3r
http://slic3r.org

Slic3r has three main areas of control: print settings, filament settings, and printer settings. Each can be saved independently of the other, allowing for a collection of presets to be designed around your most common printing needs. The simplest of these areas is the printer setup, which allows you to set the size of the printer build platform as well as details about the extruder. Generally speaking, you need just one printer setup for each printer that you want to use with Slic3r. The filament settings are also not likely to change very much, as Slic3r allows you to set the diameter of your filament and the desired printing temperature for the extruder and bed. The real power comes from the print settings, where you have almost total control over every other aspect of the behavior of the print. Under print settings, you'll find options for layer height, infill, speed, skirt and brim, support, and more.

We've discussed layer height, but the other settings are likely to be a bit mysterious. Infill controls the solidity of the print, the amount of material used to fill the interior, expressed as a percentage. The software does the math and determines how to arrange the type of infill you choose (square, hexagonal, etc.) in order to achieve the correct percentage of infill. As an example, if we were printing a 200 mm by 200 mm cube and wanted it to be totally hollow, we would set the infill to 0. Setting the infill to a very low percentage—between 1 percent and 10 percent or so—would result in a very large square or hexagonal infill on each layer. As you increased the percentage, the infill would become more and more dense, until at 100 percent infill, you would get a solid piece of plastic. You would almost never print an object at that infill, as there is a diminishing return for increasing the infill as it relates to strength versus the amount of plastic used. Over 60 to 70 percent or so and you'll likely not find any actual structural advantage unless there's a very specific geometry that needs to be solid. I find myself printing most things at under a 20 percent infill as a sweet spot of strength and weight to amount of plastic (and thus cost to print).

Speed is the speed at which the printhead moves around the build plate. FDM printing is a slow effort, and one way to speed up the process is just to make the printhead move faster as it's depositing the plastic. There are issues with simply cranking the speed up, though. As you increase the speed, there is a point at which you will begin to decrease the quality of the output. The values that are usually used in printing software to control this issue are acceleration (how quickly the printhead gains speeds) and jerk (how quickly the printhead changes direction). There's a limit to how fast you can move and extrude plastic cleanly, and each printer has a sweet spot of acceleration and jerk that produces great-looking prints as quickly as possible. The other issue that arises is that the printheads on these printers are fairly heavy, with motors and metal heat sinks and brass nozzles. As you begin to move this not-insubstantial mass faster and faster, you create a significant amount of inertia that can be more than the printer body can contain. I have seen printers literally "walking" across a desk as the printhead is thrown back and forth across the build plate.

The last part of the print settings that you want to pay particular attention to is the support material settings. This includes both raft settings as well as support settings. A raft is a thin (two- to three-layer) platform of plastic that can be printed as a sort of buffer between the build plate and the print itself. For certain prints, this can help with adhesion and curl issues. Supports are the other bit that are important in this section. Supports, as previously mentioned, are vertical structures built not as a part of the model but as a method of supporting an overhang in the model, giving the printer a base layer upon which to print the overhang in question. You can choose to have or not have supports and the type of shape they take.

Once you get all of these settings tuned for your particular printer, you won't need to change many from print to print. Slic3r supports saving profiles, so you could do a series of printer settings for the slight variations that you might do most often, such as 10 percent infill, 25 percent infill, and so on. Or if you do print with multiple filament types, you could have one profile for PLA and another for ABS, with all of the appropriate temperature changes and such preset.

CraftWare

A relatively new option in the host software front is CraftWare, designed and written by CraftBot. A plating and slicing engine, CraftWare supports any printer that speaks standard G-code. CraftWare is not open source but is available for free.

CraftWare
https://craftunique.com/craftware

Its biggest strengths lie in its impressive visualizer, which lets you manipulate and view your models from any angle clearly, and its interactive supports, which allow finely tuned control of how it builds supports into your print. It's worth trying this, as it's another arrow in the quiver of successful 3-D printing.

Simplify3D

With the wealth of free and open-source options in this software space, you wouldn't think that a commercial, closed, paid solution would last long. In the case of Simplify3D, however, you'd be wrong. Succeeding against all odds by providing a superior user experience and incredibly robust controls for your models, Simplify3D sells for $149.

Simplify3D
https://www.simplify3D.com

So why pay for this sort of program? Well, the user interface and experience have been carefully considered, and the program is both beautiful and easy to use—not a simple thing to manage. It also has abilities that are impossible or very difficult in other programs, such as full support for dual extrusion and preparing multi-filament prints. It allows complete customization of supports for difficult prints, automatically calculating them and then allowing the user to add or eliminate supports manually.

My favorite feature is how it deals with plating multiple STLs on the same build plate for printing. You can set per-STL fill details, letting you print a hollow model at the same time as one with infill, something that no other slicer supports to my knowledge. It also allows you to choose the print ordering of multiple pieces: do you want all the parts to print at once, layer by layer, or does it make sense to print all of part 1 and then start on part 2? You can do either with Simplify3D.

Not every makerspace will need to spend money on a commercial program for 3-D printing. In fact, in most cases, I would recommend against it. But Simplify3D has a very vocal fan base and is universally beloved in this space. If you have the money for a single license, it is definitely worth playing with to see if it saves you $150 worth of mistakes, ruined prints, and wasted time.

MakerBot Desktop

The company that was most responsible for introducing 3-D printing to the masses was MakerBot, and it decided early in its growth to move away from open-source solutions to proprietary ones. As a result, its printers use its own software, MakerBot Desktop, to control the printers and prepare models for printing. This software works only with MakerBot printers, and the printers work only with this software, which means flexibility and variety of interface and support are not really an option. In addition, MakerBot had a very bad few years for hardware quality and reliability.

While its most recent releases have been better on that front in that they work as described, I can no longer recommend MakerBot as a printer for libraries. Its insistence on proprietary hardware and software makes its printers much less repairable and flexible than the more open options on the market now. Libraries that have MakerBot machines can hope to keep them running, but if you are just now considering getting your library into 3-D printing, I would advise staying away from MakerBot printers.

3-D Printer Management Software

Some of the most interesting technologies to emerge in the last few years in the 3-D printing space are the variety of enterprise-style, management software programs for 3-D printing. This software is distinct from the local-control, local-management software that might be used to control a 3-D printer in the traditional way, where you have software installed on a standard desktop computer and you run an app or program that controls the printer that is plugged into it. This style of control is a level above that, operating either as a separate piece of hardware that acts as middleware for the operation of the 3-D printer, or as software-as-a-service (SaaS) that uses the web browser or a dedicated client to expose the 3-D printer to a web-based interface for control. Some of the benefits of this control for your 3-D printers include the ability to load models remotely over the web, to queue and manage jobs, to handle management of files and slicing, to receive remote notifications of activity when prints are started or completed, and to visually monitor prints via webcam. For the sort of service-oriented 3-D printer setup that many libraries have, these management layers add a huge amount of value, and I believe they are absolutely necessary as these services begin to scale.

Libraries that offer 3-D printing to the public will find huge benefits in using these management tools. From providing a public website where users can upload their models to being able to monitor prints from anywhere with a web connection, to just streaming a live video of your printer as it prints, there are numerous ways this software can enhance your 3-D printing services.

You can almost think of this management software as web-focused host software. Management software requires a dedicated device of some type to be connected to your 3-D printer in order to bridge the gap between the printer and the web, but that device can range from a desktop computer to an inexpensive Android tablet all the way down to a $35 Raspberry Pi microcomputer. We'll start with my favorite of these management tools and work our way through the top three.

OctoPrint

OctoPrint is an open-source solution for managing your 3-D printer via the web. It is my preferred management tool for remote management of a 3-D printer and provides nearly everything a library might want for making 3-D printing into a fully featured service.

OctoPrint
http://octoprint.org

While OctoPrint can be installed on a Windows, Linux, or Mac OS computer and attached to a printer, by far the easiest way to get OctoPrint running is by installing a variant of it called OctoPi, which is designed for installation on a Raspberry Pi microcomputer. A Raspberry Pi 3 costs all of $35 (plus a micro SD card for the drive) and will do everything that is needed to run OctoPrint and provide a fully featured interface for your 3-D printer. Install OctoPi, plug it into your 3-D printer, and connect to the interface via a web browser, and you can do nearly everything you might want via a simple web interface.

OctoPrint allows you to physically control your printer, move the printhead and bed, and control the temperature of both. You can control the extruder action manually and generally control all of the motors via the web. You (or your patrons) can upload STL files, set up slicing rules, queue prints, monitor the current print, and even plug a webcam in to get a live stream of the printer in action.

Even better, because OctoPrint is open source and very actively developed, it has an extensive set of plugins that can be added easily to extend its capabilities. Want to let people know how long their prints will take, how much filament they will use, and how much they will cost? There's a plugin that does all of that. There are plugins for sending alerts from the printer to just about every messaging system known to the web, including e-mail, SMS, Slack, and Twitter. And if you or your library want some other feature, it is very easy to add your own plugin to the system. One of the core plugins that I would recommend to every library is the Statistics plugin, which tracks how many prints are done on the printer, how long they take, and even energy used. If you want a way to prove usage, here's a simple way to create trackable and reportable metrics.

It's also great for creating videos of your printer in use, as the webcam controls have a built-in time-lapse function. This lets you set up a print, get it running, and come back to find a video of the print waiting for you after it finishes. Between this and the live feed, there are tons of marketing opportunities to be found using this functionality. OctoPrint also has robust access controls available so that staff can be responsible for some of the more difficult or tricky parts of the process while still allowing public access to some functionality.

The one downside is that currently OctoPrint doesn't have native support for multiple printers. You can easily run more than one OctoPi, just attaching one per printer, but that's obviously a subpar solution. It would be fantastic if OctoPrint supported more than one printer out of the box, and it is technically capable of doing so, but support for this functionality hasn't been added yet. It does have a learning curve, but there are tutorials that walk you through the worst bits, and the effort is absolutely worth it once it's running.

OctoPrint is highly recommended for libraries running 3-D printers. It's open source, freely available, and well supported in development. It will likely only be getting better and better over the next several years. Buy a Raspberry Pi and try it out.

AstroPrint

AstroPrint started as a software fork of OctoPrint, and the developers have moved it along nicely as a service for 3-D printers. It's a much more polished product and offers some interesting secondary options that OctoPrint doesn't. The primary of these is that AstroPrint offers a cloud-based slicer, where you can set up an account, upload STL files, and then choose from a long list of supported printers and material types to create your G-code file. You are then free to either download the G-code and load it directly into the printer (on an SD card, for instance) or connect your local AstroBox hardware to your printer and manage your printer entirely from the web in a similar manner to OctoPrint.

AstroPrint
https://www.astroprint.com

The company sells AstroPrint boxes directly to customers who aren't comfortable putting their own together. The code is all open source, and you can easily build your own AstroBox with a Raspberry Pi and SD card—AstroPrint even gives you instructions and such to do so. There is some difficulty, in my experience, with setting the networking up appropriately for an AstroBox. AstroBox is designed to work both with local hotspot connectivity, where a device can connect directly to the AstroBox by looking for the SSID, and to be connected to the Internet to hook up to AstroPrint's cloud service. This means that even on the most recent Raspberry Pi 3 with built-in WiFi, you need a separate WiFi dongle in order for both networks to be set up. Alternatively, you can connect the box via Ethernet and connect via your local network, but the choices here are not quite as clean as OctoPrint.

My biggest concern with AstroPrint and AstroBox is the use of its cloud services to do slicing and file management and relegating the local microcomputer controller to just a sort of terminal for the cloud account to push G-code to your 3-D printer. It's a fine setup for a single user, but because of the lack of local slicing and file management for STLs, I can't recommend AstroPrint for more than the simplest of library makerspace setups. On the other hand, it's nearly free to test and worth a day of experimentation to see if you like it more than OctoPrint for your particular needs.

3DPrinterOS

For my final recommendation, 3DPrinterOS provides a comprehensive cloud solution for managing 3-D printers. It isn't perfect, but it's the most robust cloud solution I've tested.

3DPrinterOS
https://www.3dprinteros.com

3DPrinterOS relies on a local device of some type that connects to your printer as a gateway to its cloud services. This device can be a Windows, Linux, or MacOS PC, a Raspberry Pi, or another Linux-based microcomputer, as the only real job of the local device is to communicate to the cloud and pull G-code down for the local printer to implement. All of the actual work of printer management—file management, slicing, STL editing, plating, and the like—goes on in the 3DPrinterOS cloud.

This cloud or SaaS option is comprehensive in its offerings and support for the different needs of 3-D printing. The interface centers around uploading and managing STL files, but the real strength of the platform lies in the Apps button, where you can find a host of useful tools for your models. The most useful may be the "magic fix" feature, which analyzes models for cohesiveness and fixes common modeling errors (like non-manifold surfaces and the like). The variety of slicers offers a streamlined interface for those that have many different types of printers, which will make it much easier for staff to manage. And the comprehensive statistics and cost breakdowns for prints make it easier to track and understand how your devices are being used and what your support costs look like over time.

The downsides of 3DPrinterOS, though, are many. Because it is an entirely cloud-based service, libraries without solid bandwidth or with troublesome connectivity aren't going to be happy with trying to use it. With this as your solution, if the Internet goes down, your printers aren't usable without falling back to local management software, which staff may not be as familiar with. While there is a "free" account available, in actual use, the paid accounts have features that are important and needed, and adding a subscription fee to something that you could implement at a much lower cost (via OctoPrint, for instance) is likely not an effective use of library funds. For some libraries, it may be well worth the convenience, but for most, I would suggest taking a closer look at OctoPrint and how it can be used.

Hardware

In this chapter, I'm going to list and discuss the 3-D printer companies and products that I think are most effective and efficient for library use, as well as a few experimental models that might bear watching in the future. The criteria I'm using for inclusion are popularity, ease of use, support, and the degree to which the company espouses library values of openness and information access.

This last consideration, that of values, might be a tiny bit controversial, but I believe it is extraordinarily important for libraries to consider the openness of the hardware they buy, especially for maker hardware. Some printers are designed, for instance, with digital rights management (DRM) chips built into their filament rolls that prevent using noncompany plastic with your printer. This is no different from ink-jet printers that prevent refilling ink cartridges or that have self-destruct dates on their ink even though the cartridge is still usable. It is a business model that benefits only the company and not the user, and libraries should be actively fighting against such efforts.

I'm not going to try to be completist in my listing because it would be nearly impossible to find all of the different 3-D printers on the market. By the time this actually gets to print, it will be out of date further. So rather than trying to be completist, I'm instead going to talk about the most popular in detail, while mentioning and differentiating between a number of other printers. The attempt will be made to give buying advice for libraries, taking into account the possible differences in use cases that libraries may have.

In the places I talk about build plate volume, all of the numbers will be listed as length (the *x* axis, or side-to-side in the printer) by width (the *y* axis, or back-to-front in the printer) by height (the *z* axis, or print height).

Printer Companies and Models

MakerBot

MakerBot was founded in 2009 and began its life as a member of RepRap, a 3-D printer community that started in 2005 in an attempt to make a 3-D printer that could replicate itself. MakerBot Industries has had two very different periods in the philosophy and design of its 3-D printers: the open-source period (Cupcake through Replicator) and the closed-source period (Replicator 2 through current models). In the middle of 2013, MakerBot was acquired by Stratasys, a major commercial 3-D printer company.

The printers that were produced shortly after this acquisition (the fifth generation of MakerBot printers, starting in 2014) did an enormous amount of damage to the MakerBot brand and sales. MakerBot had significant issues with its newly designed "smart extruder" that made the extruder of the printer a disposable and replaceable part. The idea was to provide more reliable printing through fresh extruders, but in reality, users saw it as a profit-motivated hardware change (other printers didn't have replaceable extruders and yet somehow continued operating). The extruders were also poorly engineered, which led to significant problems printing and huge amounts of downtime.

In the first edition of this report, I said "For the majority of libraries looking at which 3-D printer to buy, MakerBot is the right answer." This is no longer the case, and I would warn libraries away from MakerBot in general for their 3-D printing needs. Where MakerBot was once the go-to manufacturer for 3-D printers, I cannot recommend its hardware at this point. The company's move away from open-source software, combined with the smart extruder difficulties, compared to the incredibly vibrant marketplace where other printers have better functionality, makes it easy to pass on MakerBot as a supplier for libraries.

LulzBot

LulzBot is a 3-D printer company based in Loveland, Colorado that is dedicated to producing printers that are fully open hardware. It currently manufactures and sells two different models of 3-D printer, the LulzBot Mini and the LulzBot TAZ. I'll discuss both below, but in an attempt to not bury the lede, I will say up front that LulzBot is the best option for libraries looking for a 3-D printer in 2017. Its Mini is by far the best first 3-D printer for libraries, and the TAZ is the best workhorse large-format printer that I've seen. If you don't look at any other manufacturer, look at LulzBot.

LulzBot
http://lulzbot.com

All of LulzBot's work is open, which is an amazing way to run a company. Its designs are all open hardware; it runs only open source code; and it shares literally every aspect of its work openly. For a library, this means that it's impossible for LulzBot to somehow lock you into any sort of necessary relationship for support or supplies. If somehow it was to go out of business, you could still find someone to service your machine because all of the details are public, and all the parts are documented.

The LulzBot Mini is a fantastic printer and may be the best cost-to-feature printer on the market. At $1,250 before educational discount, it isn't the cheapest printer on this list, but for that price you get a rock-solid printer that includes a heated print bed and an all-metal hot-end. It's also one of the very few entry-level 3-D printers that include complete self-leveling, making the daily upkeep and tinkering minimal. You can unbox the machine and simply start printing, rather than having to spend time tinkering with thumbscrews and leveling the print bed. This eliminates so much time that other printers require that it's worth buying the Mini simply for this feature.

The Mini has a 6-inch-by-6-inch-by-6.2-inch print volume, and the hot-end design and heated bed make it possible to print almost every type of filament on the market. Specialty filaments, high-temperature nylons—nothing fazes the Mini. The PEI-covered print bed ensures the first-layer adhesion is great, and the Mini's .5 mm nozzle strikes a balance between speed and detail that works incredibly well. The Mini has a swappable printhead that can be changed out for a replacement purchased from LulzBot, which currently offers one additional option called the Flexystruder that allows for printing of flexible filaments such as NinjaFlex.

The only downside to the Mini is that it requires a computer to drive it. There is no on-board SD card reader or other print interface, which means that you'll need a laptop or desktop of some kind running Cura to send prints to the Mini. You can solve this issue with a well-placed Raspberry Pi and OctoPrint (mentioned in chapter 3, on software), which support the Mini very well (Aleph Objects, the parent company of LulzBot, also supports OctoPrint).

For some libraries, the fact that the Mini doesn't have a cover or barrier into the print area is a downside for insurance reasons. You can add an acrylic enclosure cover to the Mini through the LulzBot store, if that's a necessary part of your setup.

If you require either a larger print volume or a stand-alone printer that can be fed G-code files from an SD card, then the LulzBot TAZ 6 ($2,500 before educational discount) is your answer. The big brother of the Mini, the TAZ brings along all of the benefits of the LulzBot printers (same printhead, heated bed, PEI cover, filament variety, and more) but adds an enormous 11-inch-by-11-inch-by-9.8-inch print volume. The TAZ 6 even adds the self-leveling magic from the Mini, which makes even this huge printer super easy to deal with day to day to get great prints.

The TAZ's included SD card slot and LCD interface allow G-code files to be dropped on a memory card and the printer to print by itself, disconnected from a computer. This is very handy at times and is the one feature I wish that LulzBot would backport to the Mini.

The other really interesting feature of the TAZ is the work that LulzBot has put into producing different printheads for the device that provide all sorts of new abilities. Currently, there are four toolheads that you can buy from LulzBot in addition to the standard single extruder that comes with the machine by default. There's the TAZ version of the Mini's Flexystruder, mentioned above, which allows for the printing of flexible, rubber-like filament. The newest printhead from LulzBot for the TAZ is the MOARstruder, which has an enormous 1 mm nozzle and is designed to allow huge amounts of filament to be pushed through to the build plate for extremely rapid prototyping. This is accomplished by increasing the size of each layer, so that, for instance, a print that might be 100 mm tall that was printed with a traditional nozzle at .2 mm layer height (for a total of 500 layers) would take one-fifth as long to print at 1 mm layer height and 100 layers. This means you're cutting down a print from an hour to twelve minutes, a huge savings if you're dealing with rough prototypes.

The first of the other two types of extruders is the Dual Extruder, which is just what it sounds like, an extruder with two printheads and the ability to print two different filaments. Finally, the FlexyDually, which is a dual extruder with one drive system for rigid filaments and one for flexible, allows the printing of really interesting objects that have flexible and rigid plastic together in the same print. Imagine printing a toy car with built-in shock absorbers or a prosthetic hand with elastic joints built in. I am certain that LulzBot will continue this sort of work, adding interesting capabilities to the printer over the years.

The downside of the design of the TAZ is that it's totally open, which makes temperature control very difficult in the area around the build plate, and enclosing it is a more difficult problem due to the size. This isn't limited to the TAZ; most 3-D printers don't ship by default with an enclosed print area, but it is a downside that can affect the reliability of printing, especially with ABS or other temperature-sensitive plastics.

If your library already has a 3-D printing program and is looking to up your game, the LulzBot TAZ 6 is my recommendation for an over-$2,000 printer.

The final selling point for LulzBot printers is support, which is 24/7 and included (along with warranty service) for a year with any of its printers. For a library, knowing you have a place to call for assistance is very important, and LulzBot service has always been friendly and efficient when I have contacted them.

Ultimaker

My second choice anytime I recommend 3-D printers are those made by Ultimaker. In business for years, Ultimaker is a solid and reliable company that has been pushing the boundaries of what's possible with 3-D printing. It is also radically open, publishing its designs and software to the world for others to use, modify, and repair. Some libraries find its designs more friendly for public display, as they are mostly or entirely enclosed. Ultimaker manufactures three different printers that I would recommend for different reasons and use cases.

Ultimaker
https://ultimaker.com

ULTIMAKER 2 GO

Ultimaker's smallest and most portable printer, the Ultimaker 2 Go, is designed with mobility in mind. With a print volume of only 4.7 inches by 4.7 inches by 4.6 inches, the 2 Go is diminutive but powerful. Selling for $1,199, it does not include a heated print bed, which limits the filament types that are printable with the 2 Go. But for PLA and the like, there's no better printer for moving from branch to branch for demo purposes.

Figure 4.1
Ultimaker 2 Go Backpack

The 2 Go even has a backpack option (figure 4.1), where you can haul the printer around in a backpack based on the protective packaging that it ships in.

ULTIMAKER 2+

What I would currently call the "standard" for Ultimaker, the 2+ has a build volume of 8.7 inches by 8.7 inches by 8 inches and includes a heated print bed and fully enclosed print area. The 2+ retails for $2,499 for the standard version, and a special "extended" version, which provides more room vertically and allows for prints up to 12 inches tall, is available for $2,999. For the price, it doesn't have quite the feature set that LulzBot has, as it lacks autoleveling, and the $2,499 price is as much as the TAZ, which provides a much larger printable area.

However, people that have the Ultimaker rave about it. It is a solid, dependable printer and will provide years of service.

ULTIMAKER 3

The newest addition to the Ultimaker family, the 3 adds a ton of complexity, but this brings with it flexibility and options. It has the same build volume as the 2+, but adds dual extrusion to the mix for $3,495. This means that you can print with two filament types at the same time, in the same print. This is primarily used for very complicated geometries where you would like to print supports in a soluble filament type and the main structure in another type of plastic. This means you can print things with supports and then simply wash the supports off with water.

This would be recommended only for the library that is doing huge amounts of complicated printing and has staff to support such. These printers work very well, but they require more time and effort to keep running than the LulzBots mentioned above.

Printrbot

Printrbot makes several different models of 3-D printers and has made its name for making reliable printers extremely cheaply. They have very limited capabilities, often in terms of the filaments they can print and the size of print volume, but no other printer on this list comes close to Printrbot's pricing.

Printrbot
http://printrbot.com

PRINTRBOT PLAY

The Printrbot Play is a basic 3-D printer that has a 4-inch-by-4-inch-by-5-inch print volume and an unheated print bed, although it does have an auto-leveling function. The Printrbot Play retails for just $399, putting it well within the range of nearly any library or school that wants to experiment with 3-D printing without a huge investment. If your printing is going to be limited to PLA only, and to small items, the Play is a fantastic first printer.

PRINTRBOT SIMPLE

A step up from the Play, the Simple has nearly identical limitations and abilities, adding only a slightly larger print volume of 6 inches by 6 inches by 6 inches. This is roughly the same as the LulzBot Mini, but for literally half the price. The Simple retails for $599, and you can add a heated bed for another $150.

PRINTRBOT PLUS

The high end of the Printrbot lineup, the Plus gets big with a 10-inch-by-10-inch-by-10-inch printable volume, a heated print bed, and an extruder that can handle most filaments you can throw at it. For only $1,199, the Plus is a lot of printer for the money.

SeeMeCNC

The printers sold by SeeMeCNC are a very different breed of fused deposition printer. They are the only Delta-style printers on the list, as opposed to the Cartesian style of the rest of the pack. I'm very fond of the look of Delta-style printers and appreciate the SeeMeCNC printers for their stable and high-detail printing.

SeeMeCNC
http://seemecnc.com

ROSTOCK MAX

The Rostock MAX has a 10.5-inch-diameter print bed (Delta printer beds are measured in diameter, as they are circular rather than rectangular), with a vertical height of 14.5 inches, one of the largest overall volumes available on an FDM printer. With its heated bed, on-board SD card reader, and high-quality construction, the MAX is a great printer for a library makerspace looking to expand its offerings. Available fully assembled and ready to print for $1,899, it has a lot of print space for the money and would be an ideal showpiece unit in a makerspace due to its unusual look and movements.

ORION

The Orion is the MAX's little sister, with only a 6-inch-diameter and 9-inch-height print volume. It comes preassembled and ready to print. Other than the print volume, it is almost identical in operation and capabilities to the MAX, but for a bit of a price savings, selling for only $1,049.

ERIS

SeeMeCNC also has a smaller and less expensive Delta printer, the Eris. Having a diminutive print volume of only 4.5 inches in diameter by 6 inches tall, it doesn't have the heated bed of its larger siblings, but at a retail price of only $549, it's a neat addition to a makerspace.

The quality of a Delta 3-D printer is at least as good as (and for some geometries actually better than) that of a Cartesian style, and they are amazingly cool to watch. If you haven't seen one in action, I recommend heading over to YouTube and searching for videos of Delta printers to see one in action. I wouldn't recommend any of these as first printers or as main units for really busy makerspaces. But as a second or third printer, they are really cool and offer a new way for patrons to experiment with 3-D printing that you might find worthwhile.

Dremel

Although its name is much more associated with small rotary tools, Dremel made a big splash in the 3-D printing world with its entry into the marketplace. It did so largely by making a solid printer and focusing heavily on the needs of the educational space. It has had time in the market to release its second 3-D printer, the 3D40, and it has a robust proprietary software solution that makes printing easy to manage for all ages.

The 3D40 manages to cram a lot of useful features into its enclosed print area. It's one of the few printers to include a jam sensor for filament and include networking by default, including wireless connectivity. This allows the printer to live anywhere in your space and be reachable over the network, a handy thing that you would have to use external hardware to achieve using other printers.

Dremel 3D40
https://3Dprinter.dremel.com

With a reasonable print volume of 6 inches by 6.7 inches by 9 inches, the Dremel printer's biggest downside is that it is optimized for Dremel-branded PLA filament, and the use of any other filament (even though the printer is physically capable of using it) voids the warranty for the hardware. For a retail price of $1,599, I would expect a bit more freedom from my purchase.

It's this last limitation, the punishing of the user for going outside the Dremel ecosystem, that prevents me from fully recommending the Dremel 3D40 as a printer for libraries. From a use standpoint, it's among the easiest printers, but the way it locks down the consumable market by limiting the possible filaments that can be used with the printer (even if not using DRM to do so) isn't something that I feel libraries should be supporting.

Cubify

Cubify made a series of printers as well but is best known for its attempt to simplify the process for home users. It was purchased by 3D Systems, and in 2016, the Cube hardware was discontinued by the parent company. Because the Cube printers all used DRM-restricted cartridges of filament, they are now mostly useless since filament can no longer be bought for use in the printer.

Cubify
http://cubify.com

A number of libraries purchased Cube printers when they debuted, and they serve as a warning for others that may be tempted to buy printers that rely on proprietary consumables. Since technology is constantly changing and businesses come and go, it's important to look at purchases with their longevity in mind. Hardware that relies on proprietary consumables may be difficult to continue to support if companies decide to discontinue a product, which is why I recommend going with an open hardware printer whenever possible, as that allows for more flexibility and provides more viable options for future support.

Formlabs

The Formlabs Form 1 was the first consumer-level stereolithography printer, and its current model, the Form 2, is still by far the most popular of this type available to consumers. The build volume is smaller than that of most FDM printers, at only 5.7 inches by 5.7 inches by 7 inches, but the minimum layer thickness is only 25 microns, four times thinner than that of the best FDM printers. The Form 2 retails for $3,499.

Formlabs
http://formlabs.com

Formlabs sells a variety of types of resin that work with the Form 2, and they vary in both kind and color. The resin sells for $175 to $349 per liter, which is enormously more costly than filament used in FDM printers.

SLA printers may become far more common in libraries over the next few years, especially as competition heats up as more companies begin selling their own versions of this technology. Because they can print geometries that are difficult for FDM printers and the parts they produce are far more finished in look and feel, it's a natural progression.

Unusual Printers

There continues to be significant innovation in the 3-D printer world, especially as Moore's Law and other advances allow technologies to move down market into the consumer arena. There are companies like Desktop Metal that are attempting to bring the cost of 3-D printing directly in metals, with the capacity to print directly usable parts for aircraft and the like, down by an order of magnitude. There are also companies like BioBots, which is designing and selling a 3-D printer that can print directly in living tissue, allowing the printing of tissues for use in medical testing. The BioBot printer is currently for sale at $10,000, but that price will continue to come down over time like all technology. We can imagine a day when you might print your own living bandage for use when you burn yourself.

Desktop Metal
https://www.desktopmetal.com

BioBots
https://www.biobots.io

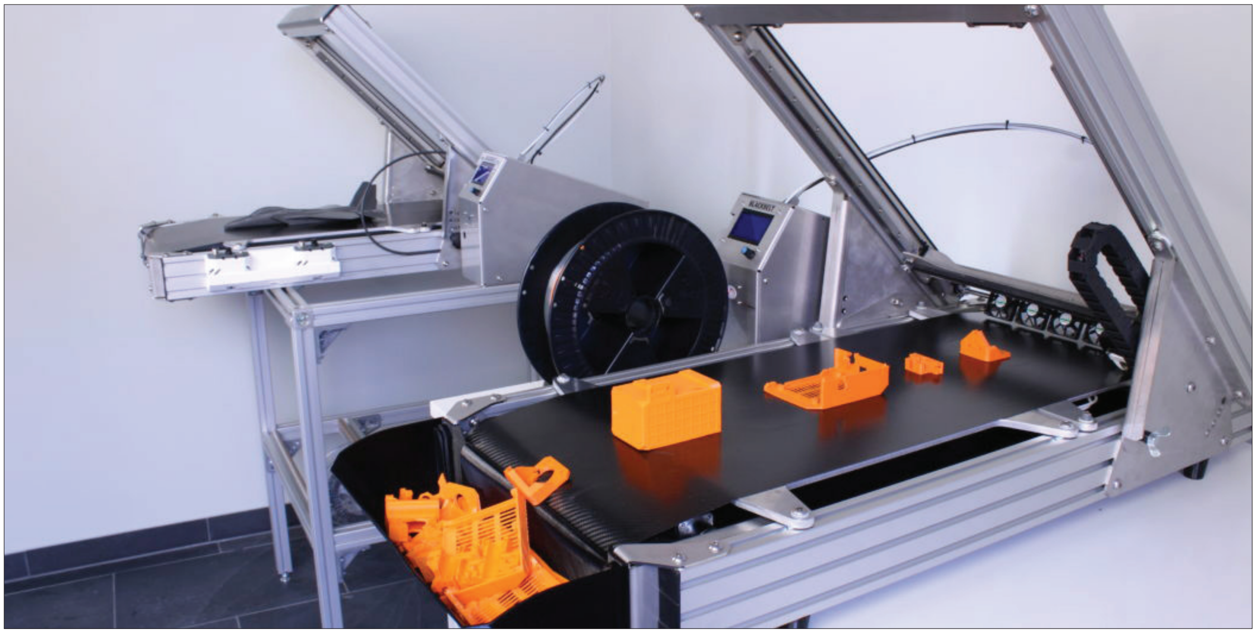

Figure 4.2
Blackbelt 3-D printer (source: Blackbelt Press Kit)

Within days of the print deadline for this issue, two very interesting new 3-D printers were announced. Since they aren't yet for sale to customers, and one of the companies is brand new and this is their first printer, I can't provide recommendations. However, both are super interesting in their own way.

Blackbelt

http://blackbelt-3d.com

Launching, as so many 3-D printers do these days, as a Kickstarter project, Blackbelt has rethought the geometry of an FDM printer to great result.

The first unique feature of the Blackbelt is the angled z-axis. The printhead is at a 45 degree angle along with the entirety of the height of the print, which allows for overhangs that aren't possible at all with a standard flat Cartesian layout.

But the really interesting advance, and where the printer gets its name, is the use of a belt as a print bed rather than a fixed plate. This gives an almost unlimited horizontal print volume, at least in one axis. The Blackbelt can therefore print things that are just not possible with other FDM printers, in both overhang and size. Among the examples that are given on the Kickstarter page for the project are the board of a skateboard and a 4-foot long sign for the company. If the company succeeds, I'm very excited about the potential for this as a high-volume printer.

Formlabs Fuse 1

https://formlabs.com/3d-printers/fuse-1/

Formlabs first burst on the 3-D printing scene with the first commercial desktop stereolithography printer and have now launched their latest original printer, the Fuse 1. The Fuse continues their efforts in bringing formerly-commercial technologies to the desktop and is the first desktop consumer-level selective laser sintering printer. The Fuse 1 doesn't use metal as a print media as many commercial SLS printers do; instead, it uses nylon powder as a substrate.

The combination of laser sintering and nylon allows the Fuse 1 to produce commercial quality parts with no limitations of geometry. Bringing this technology down to the desktop is very exciting, and I hope to see more SLS printers on the horizon.

Recommendations

There are a few different scenarios that a library might find itself in at this point in 3-D printing. Maybe you're part of a library that hasn't yet taken the plunge and are looking for how to get started, or maybe you're a library that has a printer or two and need to scale your services up to meet demand. Here are a few suggestions for setups and software to run them.

First Printer

If you've been looking for a first printer to get into 3-D printing and want to offer said printer as a service to your community, the best setup I can recommend for you is the following:

- LulzBot Mini—$1,250
- Raspberry Pi—$35
- SD card for the Raspberry Pi—$15
- two or three rolls of nGen colorFabb_XT filament—$60–75

LulzBot offers educational discounts, so if you contact the company and request one, you can have everything you need for a public-facing 3-D printer for under $1,200. Install OctoPrint on the Raspberry Pi, set it up on your network, and configure it for the Mini, and you'll have a system where a staff member can examine, slice, start prints, monitor progress, and more all from any computer on the network with a browser. The public will have the ability to load models for printing (but not actually control the printer), see the print queue, and see the cost of their print (if the library is doing cost recovery). This setup will work wonderfully and is well within the range of a small equipment grant or end-of-budget-year surplus.

If you wanted to spend the absolute minimum, but still have a reliable printer, I would go for the Printrbot Play. For $399 and a spare computer you have somewhere, you could set up a printing station for your librarians to use to make things. I wouldn't think that the Printrbot would be durable enough for huge amounts of public printing, but for getting started and understanding the technology, this is nearly as cheap as I would go.

But not completely as cheap as I would go. For the absolute cheapest 3-D printer that I could recommend trying, take a look at the Monoprice Select Mini 3D Printer. I hesitate to recommend it fully because I have not yet been able to directly test it. However, it has solid reviews online, even if some are critical of its need for regular attention. At $199.99 with a heated bed, it's a complete steal. I wouldn't expect it to last years given the pricing, but for a traveling printer or the like, $199.99 is impossible to beat for a solidly built printer.

Monoprice Select Mini 3D Printer
https://www.monoprice.com/product?p_id=15365

Fully Featured Setup

In a library where you've got a couple of printers, you're growing demand for the service, and you're looking for how to scale and enhance what you're offering, there are a couple of ways you can go. If you're looking for a printer that can really scale up and be a workhorse, especially if you're getting into more exotic filament types, the LulzBot TAZ 6 is the clear winner, especially if you feel comfortable outfitting it with a few extra specialty printheads like the Dual Extruder, Flexystruder, or MOARstruder. With a TAZ 6 and a Raspberry Pi with OctoPrint, you have a friendly and fully featured printer that will handle just about anything you throw at it, including truly large prints (entire wearable cosplay helmets, for instance) and large numbers of smaller parts plated together.

If I were planning for redundancy and volume, the other option would be to just parallelize the output by getting two Minis in the place of the one TAZ. This reduces the size of a single print you can do but increases the number of different filaments you can support.

Let's think about it in terms of budget. If you're dealing with an existing space and printer demand and have $2,500 to throw at the problem, I think the TAZ is a fantastic answer. If you have $5,000 and really want to scale, I would probably buy one TAZ and two Minis, which would give you a fantastic and reliable set of printers to use with the public. More than $5,000? I'd stick with the $5,000 answer and maybe add an Ultimaker 2 Go if I wanted to have a device that I could take out in the world easily and use on the go for outreach purposes.

And if I was looking at fully setting up a printing lab and had more than $10,000 to do so, I'd scale it out with LulzBot printers and look into either AstroPrint or 3DPrinterOS for management and control. You can always make do with a group of OctoPrint servers, but at scale they can become difficult to keep updated and manage. Once I hit five or six printers, I'd be thinking about one of the cloud-based services to handle management of files and slicing, just for ease of use.

The Case for 3-D Printing in Libraries

The question that comes up most often when I talk to librarians about 3-D printing is the very practical "Why?" question. Why 3-D printing in libraries? Why should libraries be spending money and time on providing these services to the public?

I think there are a variety of ways to answer this question, but the most straightforward is that we've always done this sort of thing. Libraries are, at their core, an engine of democratization of knowledge and information. The library as a concept is something that acts as a collective resource for the individuals of a community, and while we are best known as a resource of information, it's never been true that that is all we are. Libraries were often the first place in a community that someone could go to touch a computer and were one of the places that most Americans first saw the Internet. Those of us that were around technology in the 90s remember how amazing something as omnipresent as a laser printer was in its early days. The library was often the place that patrons would go to print their résumé because they didn't have a printer at home, and the laser printer looked so much more professional than the dot matrix printers that were more common in the early 1990s. Even farther back than the computer, the library was somewhere that members of the community went to type on a typewriter.

The point is that the library has a long, long history of providing technology for its patrons. It is still admittedly early in the life of 3-D printing, but the basic technology is affordable at this point. The future of additive manufacturing is likely to be stranger and more wonderful than I can imagine, but given the ways that even these very rough first steps are being used (in health care to print organs, in food prep to make unique foodstuffs, in art to make impossible objects), I think it's fair to say that some amazing things will come from this technology.

To give you some idea of the sorts of things that are possible with 3-D printing technology, there are hundreds of stories around the Web that are inspiring, and some that are barely believable. Here are just a few:

- 3-D printed organs are closer and closer to being a reality.[1]
- 3-D printed homes could save time and money and allow for construction in previously difficult areas.[2]
- Techniques for 3-D printing electronics could revolutionize processor design.[3]

The ultimate promise of this technology is the Replicator from *Star Trek*, a machine capable of taking the raw building blocks of matter at the atomic level and recombining them into anything you can imagine. That is obviously not happening soon, but this is how we get there, by building the simple machines that help illuminate the way.

It would also benefit libraries to have maker technology on hand and used regularly to improve their own operations and processes. While it's great to provide the technology to patrons, don't forget that libraries and librarians could benefit from it as well. Need a shelf bracket? Want to have a custom sign for your new books shelf? How about a custom sign for every month? Need to repair a random broken plastic thing? Once you have the power to create arbitrary things, the benefit is that you can create anything you can think of.

Give access to a 3-D printer to your public services department or to your circulation department, and see what they can imagine that would make their jobs easier. Then share that thing for other libraries to print. If libraries started iterating things that improve the daily tasks that librarians have to do, everyone could benefit. And 3-D printers help enable that kind of thinking—the ability to see a thing in the world and want to make it better. That's what I want to see libraries and librarians working toward.

Conclusion

Libraries have always been a place for their communities to discover new things. As technologies become increasingly important for accessing information and interacting with the world, libraries have become a place that people can go to see the new. 3-D printing is one of many technologies that are going to help to define the future in many ways, from fundamentally changing aspects of medicine to reworking the way we think about manufacturing.

At this point in its technological trajectory, 3-D printing has reached what I would consider the zenith of its hype cycle. The average person knows about it, and while they might not have used one, they are aware of it and have some mental model of how it works. 3-D printers are not the strange technology they were four years ago when I wrote the first version of this report, for example. This doesn't mean they aren't still important or that all libraries have them. But we're clearly beginning to flatten out the demand curve for them and better understand where they work and where they do not.

Note that I am not saying that every library needs to immediately run out and purchase a 3-D printer. Many already have, and more have plans to, either through staff interest or through patron demand. I think that 3-D printers, in one form or another, will eventually become as commonplace as laser printers. Not everyone will have one at home, but most people will have access to one if they need it. And a lot of that access may come through their public library.

As the technology becomes more fully featured and capable of printing more and more complicated objects, and as the prices continue to drop and drop, more and more people will see that these printers may fill a need in their lives—not owning a printer, necessarily, but just being aware of its capabilities, and being able to imagine themselves using one. That is also an opportunity for some public libraries to be ready for that potential by understanding the current state of the 3-D printing landscape.

Libraries can also benefit from having a printer for their own use. As there are more examples of libraries improving their own surroundings via making and 3-D printing, it will be easier and easier to justify a 3-D printer in your library as a resource for the library itself. In a recent study by Associate Professor Joshua Pearce from Michigan Technological University and Emily Petersen, households that purchase an open-source entry-level 3-D printer, such as the LulzBot Mini, can break even on cost in as little as six months of use.[4] Over five years, printing only a handful of objects that might be needed around the house, the study shows a nearly 1,000 percent return on investment over the cost of the printer and consumables. For a library that fully leverages its 3-D printer to improve itself, this could be an enormous savings and effort multiplier.

The hype for 3-D printers may be waning a bit in libraries. But the reality separated from the hype is that communities will continue to find 3-D printers to be an important resource, and libraries can add value to their communities by providing the service. 3-D printers can even provide a return on investment if used to solve problems around the library for the librarians and staff. Between the communities we serve and the processes and services we shepherd, 3-D printing in libraries will be around for a long time.

Notes

1. Mike Murphy, "This 3D Printer Creates Human Muscles and Tissues That Could Actually Replace Real Ones," Quartz, February 15, 2016, https://qz.com/616185/this-3D-printer-creates-human-muscles-and-tissues-that-could-actually-replace-real-ones.
2. Mariella Moon, "A San Francisco Startup 3D Printed a Whole House in 24 Hours," Engadget, March 7, 2017, https://www.engadget.com/2017/03/07/apis-cor-3D-printed-house.
3. "Truly Bringing 'Print' to Printed Circuit Boards," DragonFly 2020 3D Printer, NanoDimensions, accessed April 25, 2017, www.nano-di.com/3D-printer.
4. Emily E. Petersen and Joshua Pearce, "Emergence of Home Manufacturing in the Developed World: Return on Investment for Open-Source 3-D Printers," *Technologies* 5, no. 1 (2017): 7, https://doi.org/10.3390/technologies5010007.

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