# 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*
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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.

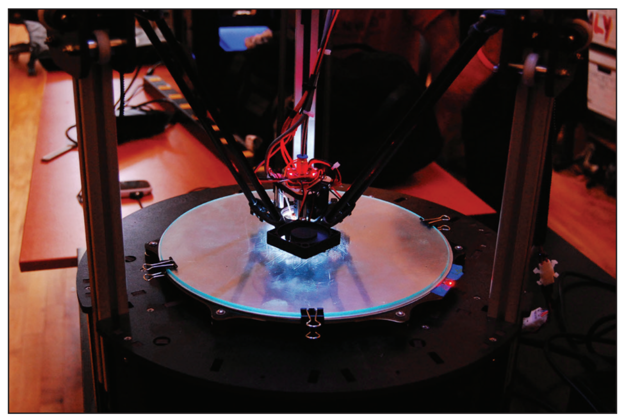

**Figure 1.2**
Rostock Max Delta 3-D printer (photo by HeatSync Labs—http://flic.kr/p/fzuDbJ; CC BY-SA 2.0, https://creativecommons.org/licenses/by-sa/2.0).

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).

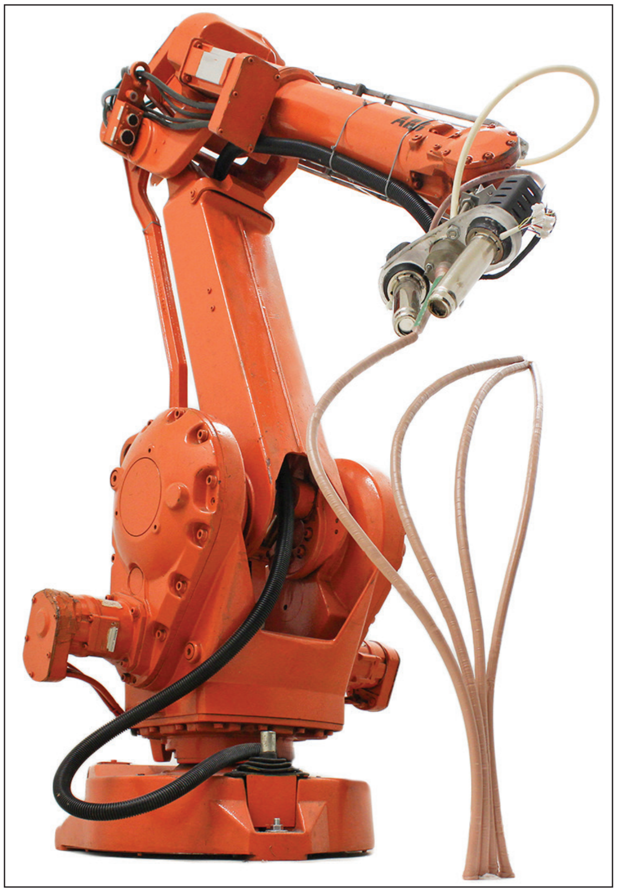

**Figure 1.3**
Mataerial multi-axis 3-D printer (source: Mataerial home page, accessed April 25, 2017, www.mataerial.com).

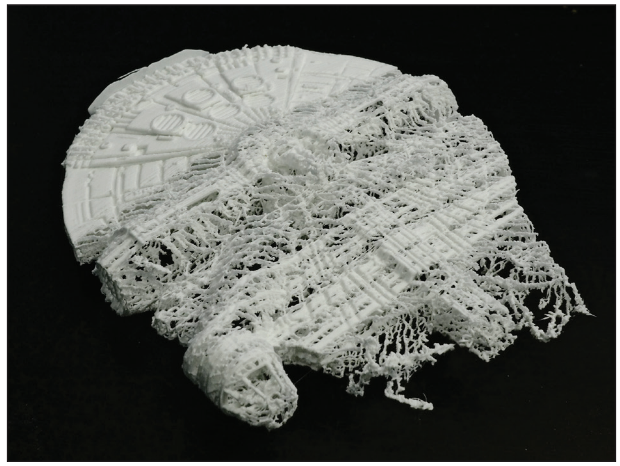

**Figure 1.4**
Fillenium Malcon fail (photo by flughafen—http://flic.kr/p/DwaefJ; CC BY 2.0, https://creativecommons.org/licenses/by/2.0).

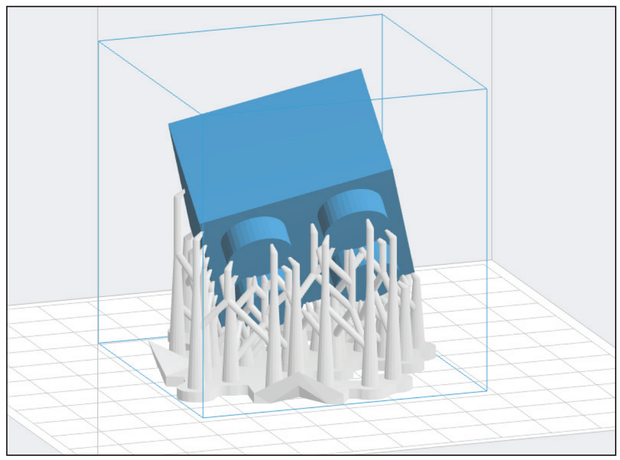

**Figure 1.5**
Support structures for a Lego block (Source: Wikimedia Commons, accessed April 25, 2017, https://upload.wikimedia.org/wikipedia/commons/1/1e/Supports_in_3D_printing.png).

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.