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— Wired

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Introduction

Are you interested in 3D printing? Interested enough to buy a 3D printer perhaps? The subject seems simple on its face, but the devil is in the details. Many manufacturers make a variety of types of 3D printers. Whether you are a basement-bound maker or a business in need of prototyping capabilities, you may be overwhelmed with the options available to you (and perhaps teasing you on Kickstarter). This report is intended to be a practical overview of the array of diverse methods and approaches which have fallen under the broad label of “3D printing.”

In the past few years, there have been an ever-increasing number and variety of commercial 3D printing systems offered by both nascent startup companies and well-established corporations. The marketing and advertising associated with these offerings usually does little to educate the consumer in the basic principles used. Because of this, consumers are often overwhelmed with the options becoming available to them.

This report is not intended to promote or endorse one 3D printer (or type of 3D printer) over any other make or model. Rather, it is meant to emphasize the strengths and drawbacks of the currently available technologies, to help narrow the field of selection prior to shopping for a specific unit. It also emphasizes open source and do-it-yourself (DIY) approaches when available. The goal is to help non-specialists find a foothold for future knowledge development, though specialists might find a few bits of new or useful information as well.

As the field has been developing rapidly (and shows little sign of slowing down now), any survey of 3D printing will likely be subject
to rapid obsolescence. With that in mind, the material contained within this report should be sufficiently generalized to provide a useful introduction to the relevant methods for the foreseeable future, providing a basis of understanding for the new and as yet unavailable methods that are right around the corner of discovery and commercialization.

**What’s In a Name?**

Before diving into the details of each method, it is worth taking a moment to address the confusion created by the (not entirely unjustified) use of technical jargon in both popular and scientific literature, as the terms *rapid prototyping*, *additive manufacturing*, and *3D printing* have been used almost interchangeably in the public discourse. This has caused some amount of confusion and debate, with many newcomers asking; “What’s the difference between these terms? Is there one?”

While arguments can be made to draw distinctions between the terms used, *3D printing* appears to be the current popularization of what once was called *rapid prototyping* and what academics have now come to describe as *additive manufacturing* (AM). Using Google Trends, Figure P-1 shows the search history for these three terms, in a sort of linguistic popularity contest from 2007-2014.

![Figure P-1. A Google Trends result for “3D printing,” “rapid prototyping,” and “additive manufacturing”](image-url)
As you can see, “3D printing” overtook “rapid prototyping” as a search term in 2011, while “additive manufacturing” is beginning to catch up to RP as well. Why the long decline of rapid prototyping as a phrase? As a basic critique, the word rapid is entirely subjective, and a fully functional part that you intend to put into service is not a prototype. The word prototype tends to have some connotation of “just for show” or “not fully functional,” a stigma that 3D printing technologies seek to transcend.

The term additive manufacturing can be contrasted with subtractive manufacturing (SM), a concise description of milling, machining, grinding/polishing, and other approaches in which material is removed selectively from a solid chunk. Additive manufacturing is the preferred term used to describe 3D printing in academic, industrial, and governmental circles.

The future of 3D printing can be seen in these terms. There is already substantial discussion of hybrid or mathematical manufacturing processes, which seek to combine additive and subtractive processes with more developed monitoring/control systems. These theoretical systems will behave something like a craftsman: making small changes to the current creation, assessing the results of each step, and correcting for errors or issues along the way. That being said, these advanced methods might not be in widespread use for a number of years and traditional machining methods still have much relevance.

**Organization and Content of This Report**

This report is not a fully detailed timeline of the development of 3D printing technologies (see Wohler’s Report for that). Instead, it attempts to generalize the types of methodologies used in 3D printing systems, to help the semi-technical reader identify and recognize the technologies that enable the 3D printing products marketed to them.

Because there are many ways to “3D print” an object, we are primarily concerned with the distinctions between the different methods used. If you have watched the recently released documentary *Print the Legend*, you will be aware of both the commercial and consumer markets and a few of their primary players, but you might not know why you would want to choose one equipment manufacturer over the other, beyond some limited assertion of quality (e.g., “This one
makes ‘better’ parts!”). This report divides common AM methods into three generalized approaches: lithography-based methods (Chapter 1), robot-controlled extrusion methods (Chapter 2), and powder-bed methods (Chapter 3). Approaches that do not fall into these groups are discussed in their own right.

Each chapter on a given printing method begins with a general overview of the operating principles employed, followed by a discussion of the materials and methods currently available in commercial and consumer products, in each case addressing the issue and logic of support structures. Following the overview is a discussion of the benefits, limitations, and upkeep required of each system. Each chapter closes by identifying primary suppliers of commercial and consumer equipment are identified, including current estimated prices.

<table>
<thead>
<tr>
<th>TL;DR</th>
</tr>
</thead>
<tbody>
<tr>
<td>TL;DR stands for “Too long; didn’t read.” In this report, a TL;DR sidebar attempts to capture one or more quick, untechnical key points for those attempting to speed-read this document.</td>
</tr>
</tbody>
</table>

After covering each type of printing method, Chapter 4 outlines unique approaches and materials that are different enough from the previously described broad categories to warrant a separate discussion. And finally, Chapter 5 offers some general guidelines for using your 3D printer, including downloading printable designs, creating your own design, or scanning an object to clone.

**Problems and Concerns Across AM Methods**

All available additive manufacturing methods share several common issues and limitations, which anyone comparing 3D printers for purchase or use should be aware of before making a decision. These problems are less relevant if you are considering only 3D printers within a certain method, but they are pretty critical when comparing different printing methods.
Surface Quality

Because most 3D printing methods involve the deposition of layers, layer height has a significant impact on the final surface quality, with thick layers creating an exaggerated terrace effect in some systems. High resolution prints require thin layers, but using thin layers requires more layers for a given object, and more layers means longer printing time. This is where the trade-off between printing resolution/quality and print time arises in most methods. The largest and most detailed print jobs can take a lot of time to produce. The final quality of the surface and the print time needed to obtain it are always at odds.

Anisotropy

As the majority of current 3D printing technologies involve some type of layer-by-layer process, the mechanical properties within the build plane are typically not the same as those measured in the build direction ("normal" to the build plane). In practice, this means that choosing several orientations for printing a part might result in parts with significantly different physical properties. For some applications, this anisotropy can be a serious technical problem, in that the traditionally produced design might need to be reengineered with the capabilities and limitations of the 3D printer’s output in mind.

Consistency

Consistency is another significant concern for all 3D printing methods. In general, obtaining a similar part every time a particular design is printed requires not just the same design manufactured using the same process, but also the same printing orientation and the same support structures. Sharing the orientation and support structure data developed for the manufacture of a particular design is not yet standard procedure, and different operators might handle a given design in different ways.

In practice, this means that you might get a slightly different result from different job shops or even the same shop, if a different machine operator happens to be running the 3D printer when your design comes up for printing again. This issue represents one of the primary stumbling blocks for trusting and using 3D-printed parts in industrial applications.
Support Structures

Support structures are often critical to achieving an accurate and successful 3D print, but the reason for their use might vary from one process to the next. As most printing methods rely on a single material, many supports are generated to be weak structures that can easily break away from the object of interest. Delicate or filigree parts that require supports are likely difficult to clean up after printing, necessitating the use of a sacrificial/dissolvable support material in addition to the primary part material, if possible.

In some processes, particularly those in which the supports are made of the same material as the final part, the removal of supports can be a substantial headache. As such, successful use of 3D printers requires skill and experience in the design of supports as well as the design of the parts themselves.
Stereolithography (SLA) 3D printing was initially derived from the lithographic techniques used in the production of microchips. At its most basic, lithography involves a thin layer of a light-sensitive goo (a photoreactive polymer) on top of a silicon wafer. This layer is exposed to a shadowed light such that selected regions (say, those exposed to the light) harden into place while the dark areas remain gooey and removable. This 2D process allows the creation of the very small feature sizes we enjoy in our integrated circuitry, and was certainly employed in the production of several electronic components allowing the composition of this text!

While industrial lithography systems might “shoot” the same patterns of light over and over again, an SLA 3D printer operates by changing the exposure pattern during every layer, so that different regions are hardened as the object is being drawn out of the bath. Figure 1-1 shows an example of this type of printer in the wild, in this case a Formlabs Form1+. 

<table>
<thead>
<tr>
<th>Process name</th>
<th>Description of method</th>
<th>Machine cost</th>
<th>Upkeep cost</th>
<th>Open source?</th>
<th>Primary distributors</th>
</tr>
</thead>
</table>
| Stereolithography (SLA) | Light hardens goop. Limited materials. | Medium | Medium | Somewhat | Commercial: 3D Systems  
Consumer: Formlabs |
There are several variations of the SLA process. You can use either a rastering laser to cross-link (harden) your photopolymer, or you can expose the entire layer at once using a projection of the current slice.

Some SLA systems are designed to draw the part out of the supply reservoir, while others are designed to submerge it in the reservoir, scraping a thin layer of liquid material across the surface. Additionally, SLA materials have been adapted for jetting through inkjet print heads derived from those used in 2D printing systems. Systems that employ this approach typically extrude and cure small droplets of
material selectively, avoiding the need for a resin bath. These small droplets of material harden before the next layer of droplets are added, in a process similar to the extrusion processes described in Chapter 2.

SLA parts often benefit from curing in an ultraviolet “oven,” which helps to strengthen the part by completing polymerization in regions that might not have had sufficient light to cure completely.

Support structures are absolutely required for SLA parts that include any design with regions that would be free-floating during the printing process (a function of design and orientation). These supports must be removed after the build process, often by hand.

SLA was the first 3D printing method, spawning the use of rapid prototyping as an industry term. It prompted the development of the STL file format used to describe 3D solid models. The man responsible for these developments, Chuck Hall, went on to found 3D Systems.

Benefits, Limitations, and Upkeep

Due to the thin layers used (high resolution), SLA has long been considered to have some of the best surface characteristics of the many available 3D printing methods. This high resolution comes at a fairly high speed, compared to other processes. In general, SLA systems might be slightly faster than other 3D printing methods when building a part of similar volume and layer thickness, because it includes fewer mechanical components, none of which are required to move within the build volume.

Perhaps the biggest drawback of SLA is the material used. Not every liquid will polymerize in the presence of light, and the materials that do are not known for their food safety. Potentially carcinogenic and otherwise not good for you, SLA resins should probably be avoided for printing out your new spork design or other components that people might try to put in their orifices (I realize this sounds odd, but it should be said for everyone's safety). Depending on the printer used, the feedstock resin might chemically attack its supply vessel, requiring replacement vessels to be purchased over time.
In addition to the equipment and the feedstock resin, additional resin vats and an occasional new light source might be required over time. A UV curing oven is often a useful piece of secondary equipment for finishing. Some hand tools might be necessary to remove supports.

**Suppliers and Pricing**

In terms of established equipment manufacturers, 3D Systems is the primary commercial SLA supplier (with models typically in the $4,900–60,000 range), while B9Creations and Formlabs were the first to deliver consumer-grade SLA systems (~$3,200–4,600 base).

The past year has seen a number of offerings funded on Kickstarter, including Titan 1, Pegasus Touch, and Peachy Printer. These young startups might yet become players in this space, though at this time there are relatively few small-scale manufacturers delivering printers. A system similar to the FormLabs Form1+ has been released in China, with some of these beginning to appear in the hands of users in the US.

A few DIY systems (some built out of discarded projection systems) have been developed and documented, though the web hosting for these instructions seems to be somewhat inconsistent.

A number of third-party suppliers of resin are beginning to appear, and Feedstock resin typically costs $60–120 per liter, with some variability among suppliers.

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**TL;DR**

SLA process: harden goop with light, in a vat or using inkjets. Pretty fast, with high resolution. Don’t make sporks or shot glasses with it.
Fused filament fabrication (FFF) systems can be thought of as simple robots with a thermoplastic extruder attached to a Cartesian (sometimes pseudo-Cartesian) gantry. The extruder lays down a thin line of polymer, drawing the desired object out layer by layer onto the print bed by following a predefined toolpath. The extruded material is not technically melted (unless something goes wrong), but it is softened to the point where it is willing to self-adhere to the similar material beneath it.

It is possible to create fine-looking but poor-quality parts, if the extruded polymer is too cold and doesn’t properly adhere to the materials underneath. The extruder is generally the most problematic part of the process, because it must operate continuously and consistently.

The vast majority of the 3D printers commonly appearing in offices, classrooms, libraries, makerspaces, dorm rooms, garages, and basements are designed to operate on the same basic principle. As they
are becoming the most ubiquitous type of 3D printer in the consumer space, they are particularly important to understand.

**Figure 2-1** shows an example of an FFF system that includes structural components printed by other polymer extrusion systems (orange parts).

![Figure 2-1. An FFF system, designed by (and with image courtesy of) Professor Tom Lauerna](image)

A variety of different terms are used to describe these thermoplastic 3D printers, the two most prominent being the open source description, *fused filament fabrication* (FFF), and the more widely used *fused deposition modeling* (FDM, a trademark of Stratasys Inc.). In support of the unlicensed description, I will use FFF here to describe the general approach, as the robot-controlled extrusion driving it has been extended to other materials (ceramics, sugars, biomaterials, etc.) without serious alteration.
The print bed can be a problematic part of the process. You need the first layer to adhere for the entire duration of the print, but you also need it to release after the print is finished. The print bed can be heated to assist with this seemingly contradictory requirement, by limiting the stress in the base layers and thereby minimizing warping and premature release of the printed part. Commercial-grade systems often use heated build chambers, allowing thermoplastics to be printed with even greater melting (technically, glass-transition) temperatures.

**Printers That Print More Printers: The RepRap Project**

Every once in a while, I’ll hear someone ask, “What if a 3D printer could print more 3D printers?” It turns out that this idea might in some sense be credited with the widespread popularity and spread of low-cost FFF 3D printing systems.

Professor Adrian Bowyer (of the University of Bath, UK), deciding that he had had enough waiting around to use the one commercial 3D printer, created an open source project dedicated to printing out a new printer of his own. Subsequent redesigns of these systems by his students and other dedicated citizen-engineers have produced a series of iterations on this design, incorporating improvements in a variety of areas, including resilience, print time for parts, construction time/complexity, and so on.

Consumer-grade FFF 3D printers are generally capable of printing polylactic acid (PLA) and/or acrylonitrile butadiene styrene (ABS). While its low softening temperature makes it unsuitable for some applications, PLA might be preferable for home and school applications, because its fumes are less toxic and it can print onto an unheated print bed covered in painter’s tape (the rougher the better — very smooth tape might not work as well). ABS and other commercial thermoplastics require a heated bed to assist with adhesion during the print.

Commercial versions are capable of printing materials that require higher extruder nozzle temperatures and higher bed temperatures, in particular polycarbonate (PC) and polyetherimide. It is not unreasonable to expect that consumer-grade systems will begin to expand into the materials currently used in commercial designs as their methods improve. The use of all-metal nozzles is a strong step
in this direction, potentially allowing consumer systems to print with PC blends in a few years.

Using supports with FFF systems can be critical for the production of designs with substantial overhangs and might help to preserve delicate designs that would otherwise sag during the production process due to gravity (even if you print upside down or sideways). If a second extruder is built into the design, a secondary material can be used to support the primary part material and selectively dissolved away after printing as part of the cleanup.

With only a single extruder, breakaway support structures might be generated automatically by the software that generates the toolpath for the print, with variable results. An alternative approach involves designing breakaway supports into the model in the first place, but this might be less feasible for some users, particularly those who are printing the designs of others and are unwilling or unable to put in the time required to modify the file. Support materials include high-impact polystyrene (HIPS) and polyvinyl alcohol (PVA), though ABS and PLA have been employed as support materials for other materials.

Many of the robots driving FFF systems can easily be modified to extrude materials other than thermoplastic (often powered by compressed air), opening the door to a variety of systems that extrude paste. Such paste extrusion systems can be used to print ceramic and glass pastes, thermosetting polymers, rubbers, glassy sugars, biologically interesting goops, foods—really, anything that will ooze properly through a nozzle when given a little push without dripping all the time due to gravity. Figure 2-2 shows a modified FFF system designed to print clay.

As many of the materials used in such systems do not require heating for extrusion or cooling for shape retention, these systems are sometimes distinguished from FFF printers by the terms robocasting or direct ink writing. Jennifer Lewis and her graduate students have been doing amazing things in this area: do look up their work!
Figure 2-2. A clay-printing FFF system, designed by (and with image courtesy of) Matthew Kenney
FFF in Metal: Electron Beam FFF

Who doesn’t want to 3D print in metal? A process similar to FFF feeds a thin metal wire into a melt pool created by an electron beam. This technology has been developed by both NASA's Langley Research Center and Sciaky Inc. and has been described by some as “electron beam welding on steroids.” This process creates a near net shape object that requires final machining and heat treatment. It might be useful for the production of large components that would otherwise be machined from a solid block.

Professor Joshua Pearce's research group at Michigan Tech developed an open source version of metal printing, with some similarities to Sciaky's methods. In their system, a MIG welder is placed above a pseudo-Cartesian robot holding a metal build platform, acting like a metal extruder.

Benefits, Limitations, and Upkeep

FFF has several benefits that seem to have assisted in its widespread adoption. While it produces some waste and stray plastic scrap (some of which could possibly be recycled with an organized effort), the materials used are fairly benign and the process can be fairly forgiving. Parts can be sanded, painted, deformed with heat, and smoothed using a vapor process, giving much flexibility to the final result. Like SLA parts, PLA parts can be used to cast metal (typically aluminum) components, using a “lost PLA method,” so a variety of DIY projects are now enhanced or enabled by access to an FFF system.

The vast majority of designs available for free online have been designed with FFF printers in mind (if they have been designed for manufacture at all). These designs range from useful household objects to absurd artistic expressions. While sometimes derided as a “trinket-making device,” the production of firearms (such as Cody Wilson's Liberator Project) has forced FFF to be taken seriously, leading to the production of DIY research devices and other components that may once have been written off as beyond the capabilities of the technology. Lead users have been experimenting with the inclusion of other components within the printed parts, and the
incorporation of magnets, electronic components, and NFC stickers have all been demonstrated.

FFF systems require fairly minimal upkeep, provided that no major mechanical problems crop up. Depending on the design and supplier, belts might require tension adjustments, and stray nuts and bolts might need tightening down from time to time. If you are not careful with the extruder nozzle (overheating, using really odd materials, crashing it into the print bed, etc.), this might be the most expensive component to replace, with the control electronics being a close second.

While the sparse infill algorithms used can create substantially lighter components, FFF printers cannot produce fully dense parts. While this is generally not considered to be a showstopper, it prevents FFF from producing transparent parts of optical quality, and the final strength obtained cannot compete with a dense injection-molded part. Additionally, FFF parts are generally not watertight, particularly in the build direction (into/out of the build plate).

Suppliers and Pricing

Due to the open nature of FFF, new suppliers are constantly appearing (and some disappearing), with new models possessing bigger build volumes, faster print speeds, and more dynamic printing options. In the commercial space, Stratasys and 3D Systems are the largest manufacturers, providing systems with large build volumes, heated build chambers, and a variety of materials to choose from (typically at $10,000–40,000).

Within the consumer space, much attention has been given to MakerBot (now a part of Stratasys), but many small startups are producing quality systems with competitive performance and price (typically $1,000–2,500). DIY kits are also available, containing all of the mechanical and electronic components required to run an open source 3D printer for $500–1,000. In a recent comparison between commercial and consumer FFF systems, the consumer prints compared favorably with the much more expensive commercial system, suggesting that savvy companies might obtain similar results at a fraction of the cost by moving toward the consumer market for their FFF needs.
Regarding the feedstock/filament costs: some systems might force their users to pay a bit more for printing material, depending on whether or not their 3D printer requires a cartridge to operate, much as 2D printers often do. FFF printers that do not meter their filament open the door to alternative suppliers. Filament quality may vary widely from one supplier to another—there have been reports of some cheaper materials leading to printing difficulties due to misshapen or excessively brittle material.

**TL;DR**

FFF/FDM: thin strand of polymer is heated and oozed onto a surface, drawing an object layer by layer. Cheap, relatively safe, flexible, and open source, it has become the go-to 3D printer for hobbyists, educators, and makers of all ages.
One of the more diverse classes of 3D printer are what I will generalize as *powder-bed processes*, though many different commercial names are applied to several specific variations of this sort of approach. You will also find them described as *granular* methods, in that powders are used rather than liquids or solid filaments.

In a powder-bed printer, two actions are repeated alternatively throughout the duration of the print. The first action involves sweeping a thin, uniform layer of powder from a reservoir across a build platform. This *recoating* step is generally performed using a doctor blade or roller, which feeds powder from a supply platform to the build platform.

In the second action, the freshly swept powder layer is selectively melted, bound, fused, or otherwise glued together. After this, the build platform lowers, and the cycle repeats itself as a new layer of powder is swept across the surface for patterning. The final result might be a solid part (perhaps fused to the build platform) or a
porous/weak part that requires additional infiltration/processing to densify/strengthen it.

**Figure 3-1** shows a powder-bed printer for the production of metal parts. As with most powder-bed systems, there's not too much to see from the outside. The door is opened to show the build chamber itself, though the interior can be accessed through the gloves in the door.

![Figure 3-1. A powder-bed printer for metal parts, courtesy of Imperial Machine & Tool](image)

After the build is complete, unused powder is carefully (sometimes less carefully) removed from the final object and recycled for reuse (if possible—some restrictions apply to recycling used powders). A final air blasting (for green parts) or sand blasting (for metal parts) is often used to remove unbound or poorly bound surface particles prior to any further polishing or post-processing.

Several methods are used to bind the powders. When melting or fusing powders together, lasers or electron beams are often employed to deliver the energy required to heat and melt the feedstock powder. Alternatively, ink jet nozzles might be used to selectively deposit a binder or glue that holds the part in place. This binder might be dyed, allowing the full-color prints seen in ZCorps (3D Systems) technology.
A notable recent reversal of the traditional powder-bed approach for metals has been described as *selective inhibition sintering.*

One element that illustrates the diversity of these powder-bed processes is the variety of materials that can be used (one at a time). Metal, ceramic, plaster, glass, and polymer components have all been fabricated using powder-bed processes, with additional materials being introduced as researchers find out what works (and what doesn’t work). Some unique systems have been developed using this approach, including Markus Kayser’s *solar sintering* system and the CandyFab project.

The need for supports varies widely from system to system. For systems that selectively bind without melting the feedstock powder, supports are often not required. The surrounding powder supports the part during the printing process and typically falls away or blows off of the printed part. In systems that do melt the feedstock powder, particularly metal processes, supports might be required to anchor the part to the plate, to prevent distortion due to the stresses that build up during the printing process. Inadequate support designs can lead to distortion and might even cause the build to fail.

**Benefits, Limitations, and Upkeep**

To grossly generalize across a diverse group of processes: powder-bed systems have a number of details and drawbacks that any potential user should consider before being overwhelmed with their well-advertised capabilities.

The fine particle sizes used in the feedstock powders of these systems allow the creation of thin layers and features at resolutions on the order of the size of the powder. Fine particles present a potential inhalation hazard. This means that powders and freshly printed parts must be handled carefully, sometimes requiring special ventilation or personal protective equipment. Most equipment manufac-

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turers offer some kind of cleanup box use to remove poorly bound surface particles using compressed air or bead-blasting.

Additional consumables might required beyond the feedstock powder. Inkjet systems will require additional binder material(s) over time, and metal melting systems will require filter changes/replacements and shielding gas (to prevent oxidation during processing).

Powder-bed systems require a volume of feedstock powder sufficient to encase the entire build volume, even if only a small amount of material is being used in the print. Because of this, the effective utilization of the powder can be fairly low for certain design scenarios. Recycling of used powder is desirable, but some materials are better suited for recycling than others. One laser-melted polymer in particular can be used only once before the entire lot must be replaced.

Due to the diversity of granular/powder systems, the benefits and limitations of each system should be compared to its direct competitors (assessing apples to apples, so to speak). For example, it is probably unreasonable to compare a direct energy metal printer (such as the Reneshaw AM250) to a selective inkjet binding system, whereas there are a number of directly comparable systems (EOS M290, 3D Systems Phenix PX, Concept Laser MLab, etc.) that would make for a suitable comparison.

**Suppliers and Pricing**

As with other methods, there has lately been an increasing number of companies developing systems that employ a powder bed. However, aside from a DIY system, there is not much available in the consumer space in the way of powder-bed systems. Lasers are expensive, mechanized stages don’t build themselves, and the associated equipment can be significant. Some DIY projects in this area appear promising, particularly the PlanB.

Machine costs of powder-bed systems are typically dependent on the type of material and binding method in use. Laser-based approaches for the binding of polymers (SLS and SLM are different names for the same basic method) generally run more than $30,000. Similar methods applied to metals generally cost somewhere in the $600,000–1.1 million range. Inkjet methods are generally much
cheaper than these laser-driven methods, and a number of legacy plaster printers are becoming cheaper and cheaper.

Feedstock powder costs vary widely from material to material, with reactive metals being some of the more expensive materials and plaster being the more inexpensive. Many users look for third-party suppliers to circumvent the markup imposed by equipment manufacturers, but the final results may vary. Not all feedstock materials are equivalent, though, so a thrifty user must be careful and well-informed regarding what they are putting into their printers.

**TL;DR**

Powder-bed systems: bind or melt layers of powder together. They might appear to behave similarly, but these systems can be very different from one another. If you are looking to purchase one of these systems, make sure that you’re comparing similar products.
There are a few rather unique approaches to 3D printing that are substantially different from the broad categories already outlined, or different enough that they deserve their own consideration independent of the more popular methods. These 3D printing processes often have a single manufacturer or are otherwise not widely represented in comparison to previously described methods.

### Laser Engineered Net Shaping (LENS)

Created by Optomec, the LENS process operates by spraying particles (typically ~100 microns in diameter) into a melt pool created by a laser beam. It is an extension of the laser cladding process, allowing a variety of materials to be deposited onto a surface that moves underneath the business end of the laser. While the process is primarily used to deposit metallic materials, deposition of glassy materials has also been demonstrated.

**Figure 4-1** shows the LENS process in action.

While the LENS process can be used to build up components from scratch, much like the other 3D printing methods, it can also be used to deposit layers onto non-planar geometries. Thus, unlike most AM methods, the LENS approach is also useful for repairing extant components and not simply for the production of new parts.
One of the more exciting possibilities of LENS is the grading of multiple materials, which can be obtained by changing the type of powder being sprayed into the melt pool. While a few AM processes allow the deposition of multiple materials, these materials typically have fairly abrupt interfaces. As many types of failure are caused by abrupt changes in material class, it is hoped that graded interfaces might create a more robust design in the future (assuming we can produce them!).

**Laminated Object Manufacturing (LOM)**

Laminated object manufacturing is one of the older approaches to 3D printing, which produces a type of composite object from individually laser-cut layers. In its most rough form, a series of paper parts are punched out and glued together by hand, with each piece representing a single layer of the final object. With a roll-to-roll process and a build region, it is possible to automate this procedure, which greatly speeds up the associated time and improves the accuracy of the final part. The final part is wood-like in behavior, assuming that paper was used for each layer.

The amount of waste created by throwing away unused paper is more similar to traditional subtractive methods, so perhaps LOM
might be considered a sort of stepping stone between traditional methods and 3D printing.

**Biomaterials and Bioprinting**

Bioprinting is an exciting subject. Who doesn’t want to print themselves a replacement organ? Indeed, the plots of several dystopian films might be discarded entirely if we could do such things, but as is often the case with such ideas, it is easier to express than to perform, for both biological and technical reasons.

One technical issue lies in the creation of vasculature. Humans typically have both large veins/arteries and small capillaries. Building a printer that can create objects at one scale or another is not too difficult, but merging them into a system that can create features at both large and small scales is difficult.

There are some commercial offerings in the bioprinter area, but it is hard to determine what these systems are truly capable of, in comparison to the custom devices created by researchers. Organovo, for example, has been offering a system for some time that is supposed to be able to make miniature livers. Anyone interested in bioprinting would probably benefit from looking into tissue culture more generally.

There has been much discussion of food printing, which might be considered a class of bio-friendly printing materials. An ever-increasing number of 3D-based food production methods have been proposed and built, though most appear to be novelties for the time being. Whether or not this is an elaborate form of “playing with your food” remains up for debate.

**Loaded Materials (Wood, Metal, Carbon Fiber)**

Within the FFF space, a number of new and strange material choices are starting to become more common. Plastic filaments (the feedstock for the FFF process) can be loaded with wood particles, metal powder, or carbon fiber, creating a final print with properties somewhere between that of its constituent components. More and more users in the consumer space are beginning to experiment with these material options as new suppliers step forward.
The use of wood-impregnated filaments (sold as LayWood) has prompted some imaginative users to vary their extruder tip temperature during the printing process, changing the resulting color and finish of the printed part. The final result is even more wood-like than would otherwise be produced and represents an interesting development in the consumer space.

**TL;DR**

There are a variety of 3D printing methods beyond the more common types, which are really in a league of their own. Who knows, maybe you or someone you know will devise a new approach.
The box arrived. You’ve got everything unpacked. The plugs are in the wall and the software has been installed. You are ready to 3D print! But what to print? Many users don’t have problems finding things they want to make (often this precedes obtaining the printer), but occasionally some are at a loss for options.

There are several methods to obtain printable files in the widely used STL format. Those described here are listed in order of increasing difficulty.

**Download It**

The easiest way to get a new printable design is to download it. A number of websites host freely available files for printing, the most well known being MakerBot’s Thingiverse. There you’ll find over 500,000 designs, with new things being added all the time.

Due to claims of censorship and a desire for more distributed systems, a variety of alternative hosting services now perform functions similar to Thingiverse. These Thingiverse alternatives include yeggi, Repables, YouMagine, and Bld3r. These sorts of STL distribution schemes are likely to proliferate in the future.

Don’t be surprised if you can’t open your STL file once you have it. Without some kind of STL viewing software, Windows will generally throw a fit, as it also uses the .stl designation for certificate trust lists. Depending on the history of an STL file, it might need to be repaired a bit before you can use it to print.
Design It

If you can’t quite find the design you were looking for elsewhere, you will probably need to design your ideal object from scratch.

A number of professional design softwares are created specifically to facilitate the design of solid 3D parts. AutoCAD, Solidworks, Catia, Rhinoceros 3D, and other platforms are often used by schools and companies to develop their designs. If you have any interest in making your own designs, you might be surprised by the number of free resources available for use, in addition to the sometimes prohibitively expensive professional design suites. Wikipedia has a great summary of both commercial and open source options available.

I will point out two of the more popular open source options. For those who have been trained to use or are used to using a graphical user interface (GUI) for designing parts, FreeCAD is an open source CAD modeling program with the capability of exporting to STL.

For those with a little bit of programming background, OpenSCAD is a free and open source modeling software that uses simple primitives to turn lines of code into a solid model. OpenSCAD makes parametric design easy to implement, so the customizable designs available on Thingiverse have generally been designed using OpenSCAD. The CubeHero blog provides a useful introduction to OpenSCAD’s operation. It describes the basic operations and illustrates their use in such a way that you can begin designing very quickly.

Scan It

Perhaps you already have a physical thing you want to clone, at least in a rough effigy. You could 3D scan it! 3D scanning technology currently takes many forms. Industrial users will opt for X-ray computed tomography for full 3D scanning of both the exterior and interior a printed part, though this equipment is generally beyond the budget of many small companies.

Laser-based scanners have been available for some time and are consistently dropping in price, including handheld models. A cheaper and dirtier scan can be obtained using an XBox Kinect or similar device, using software like Skanect. Photography-based reconstruction methods are starting to become popular, such as Autodesk’s 123D Catch program/service.
No matter what method you use to scan your object, your scan data will likely require some cleanup before printing, making 3D scanning one of the more labor-intensive methods for model development under some circumstances. Blender and Meshlab are two free and open source programs with the ability to edit point clouds and close meshes, and these are often used for cleaning up messy or defective STLs. NetFabb's software is also useful for repairing defective STL files, having some automated repair algorithms that can be quite useful.

**Licensing**

Whatever the source of your STL file, it might behoove you to be aware of the license status of the file. This is probably not a practical concern unless you begin selling the objects printed using the file, though openly hosting/sharing a design might also prompt a response from the license holder.

Most designs are released under some type of license; some form of the Creative Commons license is one of the more popular options. These licenses sometimes include clauses with a *noncommercial* component, basically allowing you to do whatever you want with the file as long as you're not profiting or otherwise taking money for it.

Going into the details of licensing options and issues is beyond the scope of this report, but certainly more has been (and will continue to be) said on the subject.

**TL;DR**

Out of printing ideas? Download something from the Internet, or design something new. Or scan something to clone, if you're brave! Just don't try to sell designs you don't have the rights to.
References

There are several additional reports and books on the subject of additive manufacturing that might be useful to the interested reader for further development. This is by no means an exhaustive list.

For a summary of developments in the 3D printing space, year by year, see Wohler’s Report.

For a general picture of what 3D printing could achieve in the future, see Fabricated: The New World of 3D Printing by Hod Lipson and Melba Kurman (Wiley).

For a summary of the types of AM methods used for producing metal objects, see “Metal Additive Manufacturing: A Review” by William E. Frazier.

Resources

There are a number of websites and online communities that will be useful to any reader who wants to maintain familiarity with the wide world of 3D printing.

3D printing news websites

- 3ders.org
- 3DPrint.com
- 3D Printing Industry
- 3D Printing.com
Communities/forums

- 3Dprinting Reddit
- Reprap Reddit
- Reprap.org

Printer comparisons (mostly FFF systems)

- 3Dprinting Reddit printerchart
- 3D Hubs 3D Printer Guide
- 3ders.org Printer Price Compare
About the Author

Dr. David B. Saint John is a researcher, educator, and technophile currently performing post-doctoral research in additive manufacturing methods at the Penn State Center for Innovative Materials Processing through Direct Digital Deposition (CIMP-3D). He has guided students and faculty in the construction of over 30 open source 3D printers and the repair of many commercial 3D printing systems, and is currently assisting industry groups in their adoption/application of methods for the additive manufacturing of metal components.