CHAPTER 1

A Brief History of 3D Printing

Enormous hype surrounds 3D printing, with predictions that it will spur a manufacturing renaissance in the United States (and perhaps the world), with everyone suddenly able to run their own cottage manufacturing facility. There are many areas where 3D printing really is creating significant change, particularly in designing and prototyping new products, in the arts, and in visualizing abstract concepts.

However, 3D printing is still a rather complex undertaking, and most users are still very much in the early adopter stage. In this book we try to make 3D printing as simple as we can, while still giving you enough of the “ifs, ands, and buts” to allow you to create sophisticated projects.

This chapter walks you through a brief history of 3D printing, with a focus on the open source consumer 3D printer technologies. In Chapter 2, we dive into the details of how consumer-level 3D printing works. Then, in Chapter 3, we talk about the open source software environment and culture, and how the field moves forward.

What Is 3D Printing?

3D printing is conceptually straightforward. An object is created by starting with nothing and adding material a layer at a time until you have a completed object. There are many natural examples of the process, and lower-tech variations have been used by other names for millennia—for example, making a brick wall.

The current 3D printing boom is really just an evolution and convergence of technologies and techniques that have been around for a while. However, there are some crucial technical and business-environment innovations covered in this chapter that came together to make consumer 3D printing affordable. To give a clear mental picture of how 3D printing works, we start with natural processes that look a lot like it.

Nature’s 3D Printers

3D printing seems like an advanced technology, but many organisms have been doing the equivalent for eons. Some of nature’s many 3D printers include the mollusks that give us seashells (Figure 1-1). As they get bigger, mollusks start adding calcium carbonate to their outer shell, which gives the growing animal more room inside. If you look carefully at seashells, you will see lines of growth.

Figure 1-1. *Seashells are a product of natural "3D printing"*

As it gets longer and wider the shell gets thicker, too, so that it does not become fragile. The shell is secreted and condensed out of materials in the creature's environment instead of laid down with a nozzle like the printers you will read about in this book, but the results can still be pretty remarkable. For more details, see `www.scientificamerican.com/article/how-are-seashells-created/`.

Similarly, many rock formations in the southwestern United States were laid down when ancient oceans built up layers of silt. The resulting sandstone has since been carved away by wind, rain, and plant roots. Figure 1-2 is an example of the final result of the processes that first build up material one layer at a time and then erode some of it away.

Figure 1-2. *Another example of natural 3D printing in Cave Valley, Zion National Park. Photo courtesy of Niles Ritter*

When people watch a natural process (like the ones resulting in the shells in Figure 1-1 or the sandstone in Figure 1-2), a few might have been inspired to create a fabrication process that will work the same way. Next, let's look at some traditional manufacturing processes that foreshadowed 3D printing.

Historical Additive Manufacturing

3D printing is a form of *additive manufacturing*. Additive manufacturing starts with nothing and builds up parts by laying up material on some sort of build platform. A lot of conventional manufacturing is *subtractive,* meaning that you start with a block of material (like metal or wood) and start cutting away material until you have the part that you want plus a pile of sawdust or metal shavings. The rock formation in Figure 1-2, as we noted, was a bit of both.

Some types of additive manufacturing have been around for a long time. A very simple example is the humble brick wall. A brick wall is built up one brick at a time, with the addition of a bit of mortar, based on either a formal plan drawn by an architect or engineer, or perhaps just built out of a contractor's head, if the job is routine enough. All the steps you will see in 3D printing are there in building a brick wall: designing a desired end product, planning out how to arrange the layers so that the structure will not fall down while it is being built, and then executing the product one layer at a time. 3D printers add the elements of robotic control to this process of building an object up a layer at a time.

Types of 3D Printers

Conceptually, 3D printers work similarly to making a brick wall (although they are a lot more flexible in what you can build). One way or another, 3D printers start with a computer model of an object and then use that model to control a robotic device that uses one of three technologies to lay up an object. Broadly speaking, there are three categories of additive manufacturing: selective binding, selective solidification, and selective deposition. Typically, people refer to these technologies by the acronyms SLS, SLA, and DLP, as discussed in this section. We are defining these three categories here to keep the sheer number of technologies understandable and to organize them a little.

Selective binding technologies make a 3D printed object from a powder (metal and gypsum are common materials) by applying binding agents or heat to fuse the powder's particles together. An example is SLS (selective laser sintering) in which a laser is used to fuse one layer of powdered material at a time. The first layer is fused to a platform, and then another thin layer of powder is added above the first, and so on as the model is built up. The powder acts as a supporting medium for the print, so that very complex and delicate prints can be created. The fine powder can be hard to deal with, though, and the printers tend to be expensive.

Selective solidification makes a solid object from a vat of liquid by selectively applying energy to solidify the liquid a layer at a time. Again, typically a first layer is created on some sort of build platform, which then moves down into the liquid (or, in some cases, a build platform pulls up out of the liquid). One example is stereolithography (SLA), which uses UV light to solidify a resin with a laser, or sometimes a digital light projection (DLP) imager, to harden a whole layer at a time. Either way, the model often needs to be cured afterwards, and the resin can be messy to deal with. Desktop SLA printers are starting to come onto the market now but are more expensive than the filament-based printers described next.

Selective deposition techniques only place material where you want it. The filament-based printers we focus on in this book work this way, by melting a filament and then placing the melted plastic to create an object precisely. There are also 3D printers that inkjet-print liquid resin, which then is UV cured. Printers that use a powder mixed with a binder are arguably a hybrid of selective binding and selective deposition.

Which technology makes the most sense for you to use depends on several things: your budget, the model's complexity, and the finest detail that is necessary. By and large, cheaper technologies produce less-detailed results, although all the technologies are evolving rapidly. This book focuses on the lower-cost end of the spectrum: printers that melt a filament and then deposit the material. The other technologies typically are not appropriate for the average home user because of cost and materials-handling issues, although this may change over time in this rapidly evolving field.

■ **Tip** If you need high resolution for your final project, you might choose to have a consumer printer at home to develop prototypes and iterate a design. You can then send a print to a *service bureau* to be printed on an expensive machine for you elsewhere and then shipped.

The term *3D printing* is actually a bit misleading because people tend to think of their 2D inkjet consumer printers and make extrapolations that are not really accurate. In reality, a 3D printer is a small robot factory. You start the manufacturing process, and (with luck!) a part emerges after a while without any human intervention. However, there are many steps involved in preparing that print; you are not just "clicking Print." Those steps and associated design decisions are the focus of Chapters 4 through 7.

The rest of this book will primarily focus on consumer-level printers that melt plastics and then extrude the plastic a layer at a time. The next section briefly reviews the evolution of these printers over the last 30 years or so. To distinguish the printers developed over the last 30 years from the more general additive manufacturing, we will use the term *robotic 3D printers*. This is not commonly used terminology, however, and after the next section we will simply call them *3D printers*, assuming the clams (and bricklayers) of the world will not object to being excluded.

■ **Tip** This chapter reviews the history and technologies of 3D printing very briefly. If you want more detail, Christopher Barnatt's book *3D Printing: The Next Industrial Revolution* (CreateSpace, 2013—available from `www.explainingthefuture.com`) contains good reviews of the various technologies, their histories, and how they work.

The Early Days of Robotic 3D Printers

Charles W. (Chuck) Hull is generally credited with developing the first working robotic 3D printer in 1984, which was commercialized by 3D Systems in 1989. These machines were SLA systems (described earlier in this chapter), and many large commercial machines still use this technology. Other early work was taking place at the Massachusetts Institute of Technology (MIT) and University of Texas.

A flurry of patents followed in the early 1990s for various power-based systems. These systems squirt a binder very precisely on the surface of a vat of powder to create layers (again, with a downward-moving platform). Alternatively, a laser can be used to fuse the powder together (in SLS, as explained earlier in this chapter). SLS patents became the basis for Z Corp, another early printer company that created large industrial printers. Z Corp is now part of 3D Systems.

Meanwhile, S. Scott and Lisa Crump patented fused deposition modeling (FDM) in 1989 and co-founded the printer manufacturer Stratasys, Ltd. This technology (more generically called FFF, for fused filament fabrication) feeds a plastic filament into a heated extruder and then precisely lays down the material. When key patents expired in 2005, this technology became the basis of the RepRap movement described in the next section.

There are 3D printing technologies that can print at the molecular level (called *two-photon polymerization*, which uses femtosecond pulsed lasers to fuse a powder). These are documented mostly in scientific literature at the moment. At the other extreme, it is possible to print large concrete structures (*contour crafting*, developed at University of Southern California and described at `www.contourcrafting.org`). Researchers are printing food and even human organs. Chapter 14 covers more advanced technologies.

The pace of development in the field is very rapid; new methodologies are being invented both by commercial companies and by academics, and it can be a real challenge to keep up with it all and distinguish between a new capability and a dubious idea.

The RepRap Movement

When some of the key patents expired on the FDM printing method, it occurred to Adrian Bowyer, a senior lecturer in mechanical engineering at the University of Bath in the United Kingdom, that it might be possible to build a filament-extruding 3D printer that could create the parts for more 3D printers (besides readily available electronic and hardware-store components.)

Furthermore, Bowyer published the designs for the parts for his 3D printer on the Internet and encouraged others to improve them and in turn post the improved versions. He called this open source concept the RepRap project and obtained some initial funding from the UK's Engineering and Physical Sciences Research Council.

Bowyer's team called their first printer Darwin (released in March 2007) and the next Mendel, released in 2009 (for more details, see `http://en.wikipedia.org/wiki/RepRap_Project`). The printers were named after famous evolutionary biologists because they wanted people to replicate and evolve the printers. Files to make the plastic parts were posted online, freely available, with alterations and improvements encouraged. Necessary metal parts were ideally available at a hardware store or able to be made in a garage. In practice, nozzles were available for online purchase pretty early on for people without access to machine tools to make one, and stepper motors were commodity items.

The early printers were difficult to put together and to get to print well. In the Czech Republic in 2010, Josef Prusa released a design now called the Prusa Mendel. It simplified the original Mendel design, and after that there was an acceleration in printer designs as people tried out the open source designs, modified them, and posted their own. A "family tree" of this period can be found at `http://reprap.org/wiki/RepRap_Family_Tree`.

Then there was a transition from making files for printer parts downloadable to making whole printer kits available for purchase. One of the better-known kits was the MakerBot Cupcake CNC, which started shipping in April 2009. It was superseded by the MakerBot Thing-O-Matic in 2010. These were mostly made of lasercut wooden parts with some 3D-printed parts (plus, of course, motors and electronics). Eventually, MakerBot became one of the earlier commercial consumer printer companies and was purchased by Stratasys in 2013.

What really caused a blossoming of different designs, though, was *crowdfunding*—websites that allow entrepreneurs to put out early stage products and take contributions from the public to fund development and early production. Because key patents for the core technologies underlying filament-based 3D printing had run out, entrepreneurs typically did not have any type of proprietary technology, which made traditional startup funding difficult to obtain. In the next section, you will see how the availability of crowdfunding enabled 3D-printer entrepreneurs to launch their startups.

The Rise of Crowdfunding

By 2009, 3D-printer development largely split into two camps: those supplying large, industrial printers (typically with some proprietary technology) and a big informal network of people working on open source RepRap or similar filament-based consumer printers.

On April 28, 2009 the Kickstarter crowdfunding platform launched (`www.kickstarter.com`). Kickstarter is one of many crowdfunding platforms that allow an entrepreneur to post a project and ask people to support the endeavor. Various crowdfunding platforms have different rules about the type of projects that are acceptable, and open source 3D printers are a very good fit for crowdfunding because most crowdfunding sites require a clearly defined project. Developing a 3D printer is a project with a natural endpoint, and often a printer is the reward the donor gets for supporting the development.

■ **Tip** To see the vast variety of technologies on the crowdfunding platforms, go to their sites and search on "3d printer" for printer projects and "3d printing" for ancillary technologies and design projects on Kickstarter (`www.kickstarter.com`) and Indiegogo (`www.indiegogo.com`). This material literally changes every day, and watching projects posted on these platforms is a good way to see what is being invented on the entrepreneurial side of the 3D-printing ecosystem.

In 2012, the Form 1 stereolithography printer raised nearly $3 million on Kickstarter; in 2013, the Buccaneer filament-based printer raised about half that. Many other 3D printers have raised funding in the six figures on Kickstarter and other platforms. An ecosystem of related projects—such as printing different types of objects (jewelry, dolls, and so on) and post-processing technologies—has appeared on Kickstarter.

■ **Caution** Crowdfunding platforms do little or no review of project feasibility. You need to evaluate for yourself how likely it is that a device on a crowdfunding site will actually ever work and remember that you are backing an entrepreneur, not ordering something from a department store. Crowdfunded products may appear years late, or not in the form envisioned.

Enabling Technologies

The confluence of expiring patents on core 3D-printing technologies and the emergence of crowdfunding platforms created a ripe business environment for small inventors to get 3D printers and related products to a wide audience with very little capital. Any sudden wave of innovation like the current one in 3D printing has many components, but the development of two technologies—the Arduino and open source code repositories—had an outsized impact on the 3D-printing ecosystem.

The Arduino

In 2005 the Arduino open source microcontroller and its integrated development environment (IDE) were introduced, based on a project at the Interaction Design Institute in Ivrea, Italy. Arduinos were designed to be easy-to-program hardware/software environments for student projects, hobbyists, and the like. As it turned out, an Arduino board was also just about the right computing power to run a consumer 3D printer. Low-cost, open source, and adaptable Arduinos and their associated hardware ecosystem enabled easy system development of what might have otherwise been prohibitively complex machine control systems.

Open Source Code Repositories

Github (`https://github.com`) launched in 2008. It is a platform that allows software developers to work together; accounts for people working on open source projects are free. An easy-to-use system of software repositories made it easy and seamless for developers to build on each other's designs. Open source software projects existed decades before this, of course, but the Github environment made it simpler and cleaner for people to work together than before.

Many *wikis*—websites for sharing information among community members—exist as well (including the RepRap wiki at `http://reprap.org`). Wiki technology is much older (the first one launched in 1995, according to Wikipedia's entry on wikis) but has been a crucial part of the infrastructure development for consumer 3D printing. Chapter 2 is a discussion of open source 3D printer software.

A Case Study of Printer Evolution

If you look at the "family tree" of RepRap printers, it can be pretty overwhelming. We will follow one branch which leads from an early classic RepRap design to a successful Kickstarter-funded printer as a case study of open source printer evolution.

Figure 1-3 shows the two printers: the modern Bukito (www.deezmaker.com) and the RepRap Wallace (http://reprap.org/wiki/Wallace). The man holding the two printers is Rich Cameron, who designed the Wallace in 2011 and was a crucial member of Deezmaker's Bukito team in 2013–2014. He goes by the "nom du internet" *Whosawhatsis*, and so you may find his designs by searching on that name. (He is also the technical reviewer of this book.)

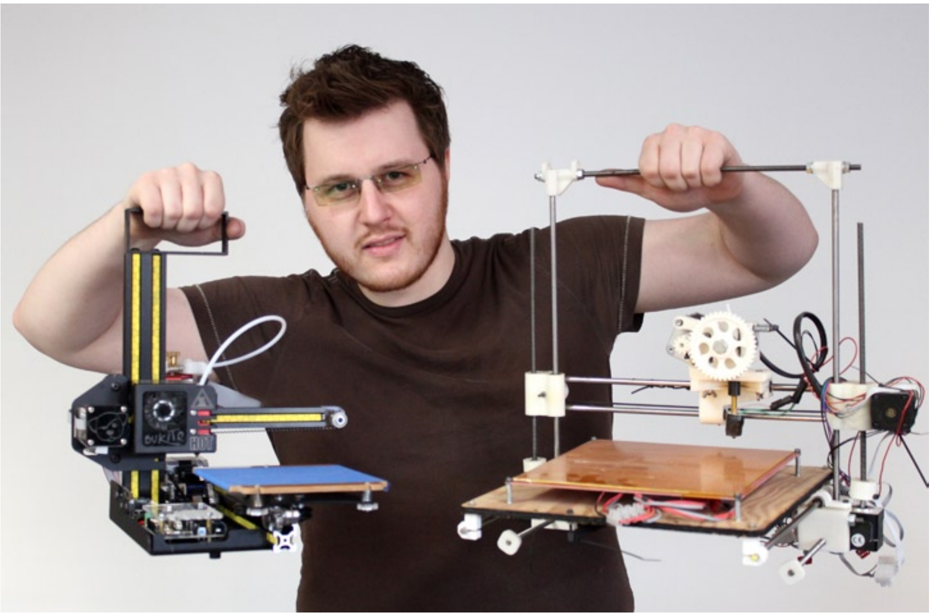

Figure 1-3. *Rich Cameron, aka Whosawhatsis, holds a Deezmaker Bukito (left) and its ancestor, a RepRap Wallace (right). Photo by Diego Porqueras*

It is quite stunning to look at Figure 1-3 and see how rapidly open source printer design has matured in a little over two years. The Wallace (named after evolutionary biologist Alfred Russel Wallace) was loosely based on the earlier Printrbot. Cameron adapted the design using OpenSCAD (which you will learn about in Chapter 5) to be simple yet robust and able to be configured in various sizes.

Cameron did not sell the Wallace; he posted the part designs on http://reprap.org/wiki/Wallace. Builders were on their own to source the parts. For a while, a German company sold a version of the design with resin-cast versions of the parts that otherwise would have been 3D printed.

The Bukito was a Kickstarter project managed by Diego Porqueras that raised $136,984 from 307 backers in a campaign that ended August 4, 2013. The Bukito will be sold in kit form by Deezmaker, a small company in Pasadena, California, where Cameron is now VP of Research and Development. Because 3D printing parts is still slow, to be able to meet demand the Bukito has few 3D-printed parts (versus the large number visible on the Wallace) and more traditionally manufactured parts.

There are now dozens of 3D-printer companies, ranging in size from public companies like Stratasys, Voxeljet, ExOne, and 3D Systems (which acquired another large player, Z Corp, in 2012) to tiny organizations with a handful of people. Some printer companies started out open source but evolved proprietary systems for either their hardware or software; others have worked to stay open source. Some have tried to keep the printed-part count up; others have bowed to the inevitable as their production runs got larger and moved to more conventional parts.

There would not be a 3D-printing industry without customers. Professional designers and artists have been early adopters. However, there also has been a rise of hobbyist users associated with a social phenomenon known as the *maker* movement, which can loosely be defined as a social trend toward making things yourself, preferably things that are rather hard to make. This maker ecosystem is discussed in detail in Chapter 3.

Summary

In this chapter, we briefly reviewed how the 3D-printing industry has gotten to its current state. We focused in particular on the open source RepRap heritage printer and how it is rapidly evolving and maturing. In Chapter 2, you will learn more about the typical hardware of a RepRap heritage printer, and in Chapter 3 you will study state-of-the-art open source software.