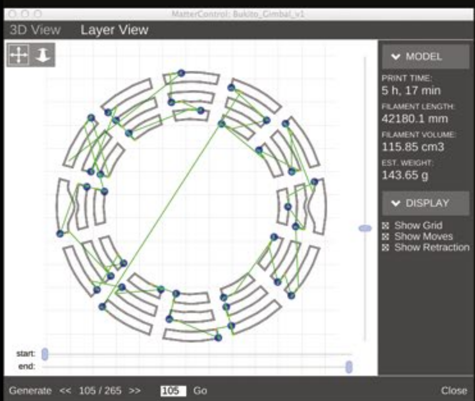
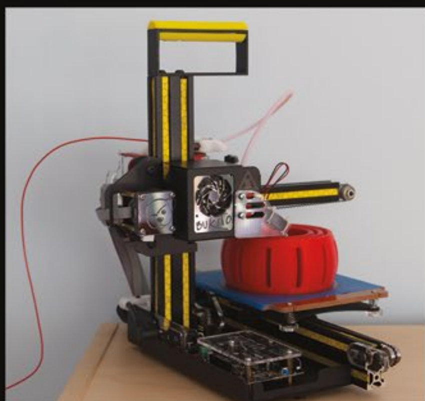
TECHNOLOGY IN ACTION™

Mastering 3D Printing

MODELING, PRINTING, AND PROTOTYPING WITH REPRAP-STYLE 3D PRINTERS





Joan Horvath

Deezmaker 3D PRINTERS

For your convenience Apress has placed some of the front matter material after the index. Please use the Bookmarks and Contents at a Glance links to access them.

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Contents at a Glance

Introduction

3D printers have been around for about 30 years, but you would never know that from the current explosion in both 3D printers and the uses for them. Although some of the more extreme hype in the field will go away in due course, 3D printing really does enable some new ways of thinking about creating products, particularly custom ones. What is new is the availability of low-cost 3D printers (costing from a few hundred to a few thousand dollars). These lower-cost machines have the promise of making the front of the product-development process much more efficient and enabling distributed manufacturing. This book focuses on these consumer-level printers and their applications. In particular, the emphasis is on open source 3D printers—machines whose software and hardware designs are freely shared online.

3D printing can be defined pretty simply: creating an object by building it up layer by layer, rather than machining it away, the way you would by making something from a block of wood, or squirting something into a mold, as you would for injection-molded plastic parts. Its flexibility and the sheer magic of seeing something built from nothing have captured people's imaginations, and it is clear that surprising applications will continue to pop up for years to come.

This book is intended for several audiences. First, it is meant to be a self-contained tutorial on consumer 3D printers and the open source software that runs them. The field is changing very rapidly, though, and as such you should expect that the details of the software and hardware will shift away from the book's descriptions. A recurring metaphor you will see in this book is that 3D printing is about as complex as cooking. In cooking terms, you will find that this book has a bias that shies away from providing recipes to follow exactly and instead leans toward teaching you how to cook over the long haul.

This book also is intended to be used as a text for a semester-length class or university extension certificate series covering 3D printing, its applications, and its place in manufacturing innovation. It might be paired with an in-depth class on 3D computer-aided design (CAD) software for students interested in engineering and industrial or product design applications. Similarly, it might be paired with in-depth instruction in one of the sculptural 3D-modeling programs for students developing skills in 3D animation or fine art.

Part 1 (Chapters 1–3) of the book gives background on the history of these printers, talks about how the hardware works, and gives some insight into the open source and do-it-yourself movements that nurtured the propagation of the consumer 3D-printer industry. Part 2 (Chapters 4–8) is the nitty-gritty tutorial on the workflow of using a 3D printer: developing a 3D model, slicing it into layers that the printer will create one at a time, and controlling the printer in real time. Part 2 also reviews available materials and walks through some case studies. Part 3 reviews how you can take your 3D print and post-process it to improve the surface finish, create larger projects, or even cast a metal part from your printed one. Part 3 covers troubleshooting, too, just in case you got a little too ambitious for your printer's linking . Finally, in Part 4 you will read about how educators, scientists, and others are using 3D printers, and where the field may go in the future.

If you are just starting your exploration of the field, welcome. Hopefully, this book will be a good guide for you, and you will finish it ready to take on challenges and try to help build this new frontier along with us.

PART 1

Open Source 3D Printers

The first part of this book introduces you to open source 3D printers. A user makes a number of tradeoffs choosing an open source, "hackable" design, and these tradeoffs and the design rationale behind them are the focus of the first three chapters.

Chapter 1 is a brief history of 3D printing, with a focus on consumer printing. Chapter 2 talks about how these printers work and why there is a sudden blooming of interest in the technology. Chapter 3 rounds out this section with a discussion of the open source philosphy and the pros and cons of being a part of an open source 3D-printer community.

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.)

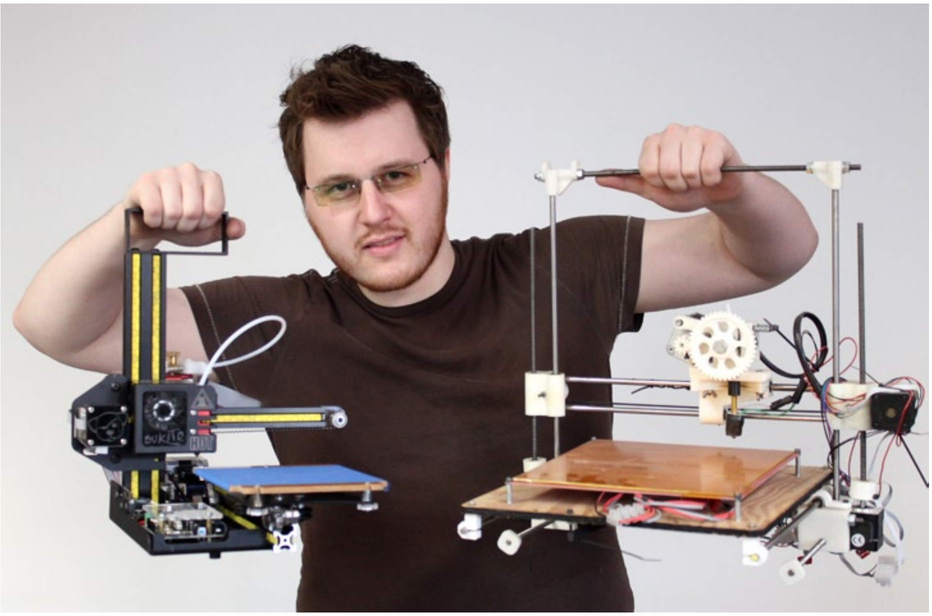

Figure 1-3. *Rich Cameron, aka Whosawhatsis, holds a Deezmaker Bukito (left) and its ancestor, a RepRap Wallace (right). Photo by Diego Porqueras*

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.

CHAPTER 2

The Desktop 3D Printer

In Chapter 1 we saw that 3D printing has a 30-year history spanning a variety of technologies. The most notable development of late has been the dramatic drop in cost and availability of 3D printers. This has been driven by the technical, legal, and societal shifts in the 3D-printing market since the major patents in the space started to expire over the last decade. Printer manufacturers now range in scale from public companies to crowd-funded (or bootstrapped) entrepreneurs.

This chapter introduces the consumer-level desktop (or perhaps, more accurately, *benchtop*) 3D printer, the major types of printers, and a bit about how they work. Then in Chapter 3 we will learn more about the open source movement, the maker phenomenon, and the business and social environments driving the rapid expansion of this market.

Who Uses Consumer 3D Printers?

Why would any normal consumer want a 3D printer? Many early adopters have been hobbyists who just want to try out the technology for its own sake. They have driven printer design forward by contributing to open source forums. The stereotypical use of a printer in the hobbyist sphere has been to print out toys, tool holders and organizers, science-fiction character figurines (Yoda heads are particularly popular), role-playing game objects, abstract mathematical sculptures, and add-on or upgrade parts for 3D printers themselves.

However, early adopters with critical applications are also starting to emerge. Product designers, Hollywood special-effects artists, and others who frequently need one-off models can use a 3D printer to make a physical model that is much easier to alter and iterate with clients than a traditional foam-core or clay one.

Chapter 9 discusses the process of integrating traditional manufacturing technologies like sand casting with 3D printing to create prototypes in metal more efficiently than is possible with traditional sculptural techniques. Small-run production also can benefit from using a few 3D-printed parts; many startup 3D printer companies use at least some 3D-printed parts for a while until their production runs reach a point where other processes make more sense. The large white parts in Figure 2-1, for example, are 3D printed.

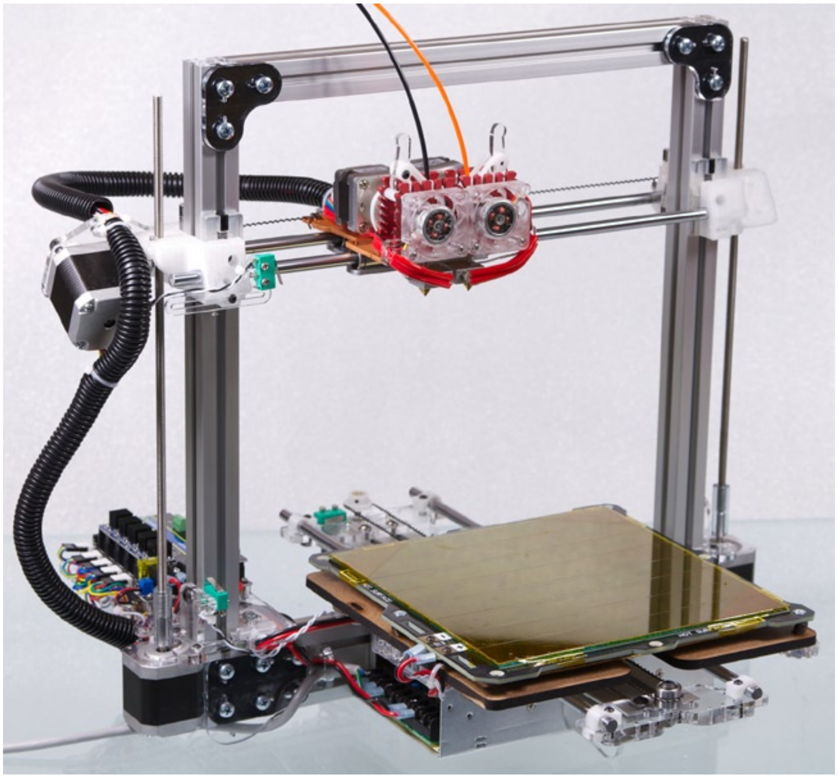

Figure 2-1. *A typical Cartesian 3D printer (a Deezmaker Bukobot Duo). Photo courtesy of Deezmaker*

At the other end of the product lifecycle, 3D printing has also found a niche in making parts to keep discontinued or obsolete equipment going a while longer. Odd-shaped fittings and brackets that are no longer made can be recreated in a computer-aided design (CAD) program and then printed. Unfortunately there's no easy way to "make a copy," particularly if the part has a lot of complex holes and internal structures that a scanner cannot illuminate well. A lot of endeavors in this area are underway, however, and by the time you read this, better solutions may be available. Chapter 4 covers the process of creating a model by developing one, scanning it in, or finding a version that has already been created online.

Personalization has also been a popular use of 3D printers. Cellphone cases are the stereotypical use here, and the online databases of objects (as described in Chapter 4's section "Downloading and Modifying Existing Models") contain a vast array of options. Once people get proficient with design software, they also start to use their printers to solve small household problems that otherwise would use duct tape and random leftovers from other projects. Little brackets to hold things in place and replacements for broken knobs, for example, are good uses.

The author's husband's first project was to create a stand to hold a container of his favorite (but rather viscous when cold) ice cream topping upside-down in the fridge so that it would always pour easily right away. Although his was a bit of a first-world problem, you can imagine that assigning a similar problem to students would be a good design exercise that could use several different disciplines.

Educators and scientists have always created models to illustrate mathematical and scientific abstract concepts; organic chemists have long wandered around campuses with construction-toy molecule models. 3D printing (and the ability to easily share and build upon models, as discussed in Chapter 4) makes the technology a natural for educational and scientific uses. In Chapter 12 we will see how educators use 3D printers, and Chapter 13 talks about some scientific visualization uses.

Types of Filament-Based Consumer Printers

As mentioned, because of their convenience and ubiquity, this book focuses on printers that melt filament (spools or cartridges of material, typically either 1.75 mm or 3 mm in diameter) and lay the melted material up layer by layer to form objects. But there are now consumer-level resin printers, including those from Formlabs and B9Creations. Using one of these is significantly different from using a filament-based printer. If you have purchased an open source resin printer (such as the B9Creator), you will be able to extrapolate your processes, to a degree, from those described in this book.

The RepRap movement discussed in Chapter 1 resulted in a blossoming of different models of small, relatively low-cost 3D printers that melt and extrude plastic filament. Most filament-based desktop 3D printers on the market currently are *Cartesian*. These machines have a frame that is more or less rectangular (or at least made up of pieces at right angles). Various parts of the printer move along each of the axes to create a 3D print. (Both printers shown in Figure 1-3 are Cartesian.) Although Cartesian printers move along right-angled *x*, *y*, and *z* axes, they frequently have diagonal supports (for example, the RepRap Mendel and its descendants).

Although Cartesian printers are the most common, there are others that are not designed to move in three right-angled axes. There are several types of non-Cartesian 3D printers. One interesting non-Cartesian branch of the 3D printer family tree is the *Deltabots.* Their heritage is from pick-and-place industrial robots used in industrial applications to precisely place a part on an assembly or in a package. The following sections compare the Cartesian and Deltabot design philosophies.

■ **Note** Deltabots are the single most common subcategory of non-Cartesian, inverse-kinematics driven printers, which also includes SCARA (Selective Compliance Assembly Robot Arm) bots, polar bots, and some more obscure concepts (most of which are developed by Nicholas Seward—`http://conceptforge.org`). Seward's designs are well known in the RepRap community for using complicated *inverse kinematics* more complex than the standard delta/SCARA designs (Deltabots are explained in an upcoming section). Inverse kinematics algorithms start with a position for the print head in space and work backwards to figure out where the non-Cartesian arms should go to get the print head there.

Cartesian Printers

Figure 2-1 shows a Deezmaker Bukobot Duo, a typical Cartesian, RepRap-heritage 3D printer. 3D printers define *x*,*y*,*z* axes. Typically, the *z* axis is the vertical one. In the case of the machine in Figure 2-1, the *x* axis direction is from left to right, and the *y* axis is toward and away from you.

Figure 2-1's design has a build platform (the square platform, where the 3D-printed object will build up) that moves in the *y* axis (forward and backward in the view in the figure). The build platform rests on the *Y carriage* which moves the platform along the *y* axis.

The mechanism partway up between the build platform and the top of the frame is the *X carriage*. The X carriage carries the *extruder.* The extruder in turn has several major components. The *extruder drive mechanism* drives the filament into the *hot end* where it is melted and extruded through the *nozzle.* In Figure 2-1's design, the extruder moves left to right to create the motion in the *x* direction. The whole X carriage is moved up and down by the motors and screw gears visible on either side to give motion in the *z* (vertical) direction. Or, to put it another way, the Z carriage is the entire *x* axis.

In later sections of this chapter we will talk about each of these components. For now, the thing to notice is that everything is at right angles. Each motor drives one axis (there are two motors on the *z* axis to help lift the *x* axis while keeping it level—if there were only one motor on one side of the frame, it would be difficult to keep the *x* axis level).

This design (called a *gantry*, an overhead axis supported on both ends) has the virtue of conceptual simplicity: if you want to move on the *y* axis, just one motor has to engage. (The *y* motor is at the back of the machine here and not visible under the build platform; the *x* motor is the motor at an angle on the left side of Figure 2-1). Different manufacturers make various choices about which axes to move and which parts to keep stationary. Many use the arrangement just described, but some others move either the extruder or the platform in both *x* and *y* directions. A Cartesian printer does not have to have a rectangular frame. An open, cantilevered, gantry-style frame (as shown in Figure 2-2) accomplishes the same thing. Because the frame needs to be very stiff to keep the precision of the print high, a gantry is best for smaller build area printers where the extruder is not suspended too far out on a beam.

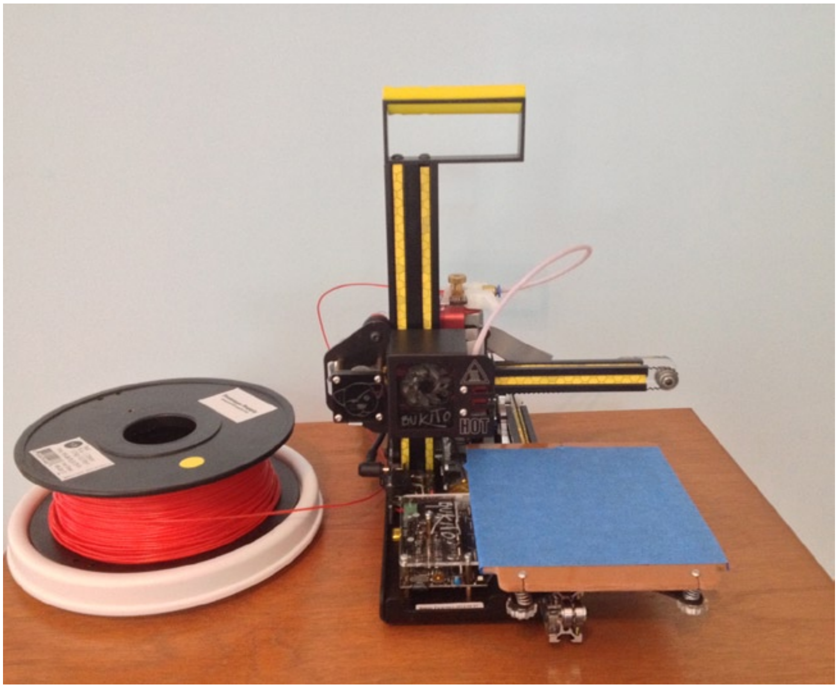

Figure 2-2. *A cantilevered, gantry-style Cartesian 3D printer (Deezmaker Bukito)*

Figure 2-2 shows a Deezmaker Bukito 3D printer, which has a 5×6-inch platform and a maximum height of 5 inches. (By contrast, the printer in Figure 2-1 was designed to print objects up to those that fit into an 8-inch cube.) This machine moves the extruder from right to left (*x* axis), moves the platform forward and back (*y*), and carries the whole *x* axis up and down to get the *z* (vertical) dimension.

Deltabots

The Deltabot design (Figure 2-3) is an alternative to the Cartesian. The extruder is attached to an end effector at the intersection of three carriages. The carriages move in tandem for *z*-only motion, but *x*-*y* motion (the plane parallel to the build platform) is controlled by their relative positions, so they spend more time moving in opposition to one another than in tandem. The carriage geometry is set up such that the extruder will move in *x* and *y* keeping the nozzle pointed straight down at all times. This type of Deltabot is called a *linear delta robot*. For applications other than 3D printing, rotational actuators are more common than linear actuators.

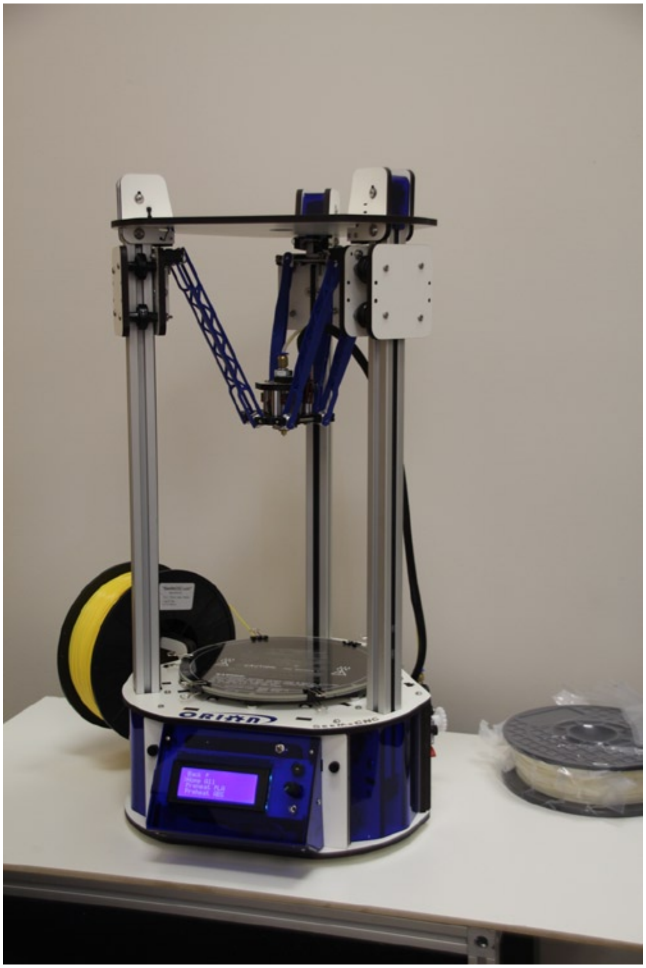

Figure 2-3. *A Deltabot 3D printer (the SeeMeCNC Orion). Photo courtesy of SeeMeCNC*

Deltabots carry very little weight on the end effector and can therefore move very fast, and a lot of the mechanisms are mature from their pick-and-place robot heritage. There are also not a lot of constraints on how big the machine can be. Determining the theoretical resolution of a print in the *x-y* plane is more complex for a Deltabot than for a Cartesian.

As with all things in 3D printing, there is a lot of work ongoing in this sphere, and you should expect both Cartesian and Deltabot geometries to continue to improve. The layer-height-versus-accuracy discussions in the remainder of this book are focused for the most part on Cartesian geometries.

■ **Note** A Deltabot's motion is hard to describe and fun to watch, so if you are having trouble imagining how this works, search online for "deltabot 3D printer" videos.

Kits vs. Assembled Printers

Many 3D printers are sold as kits, and you assemble the printer. This has the virtue that you end up understanding the printer and how it works as a system much better than you would had you just bought the system off the shelf. Putting together a kit enables you to be better prepared to make adjustments in hardware and software later on, because the reality is that, to be able to print well, most printers require significant knowledge of how the system works.

The counterargument of course is that someone (or some robots) who assemble electronics all the time are more likely to do a good job than you are. This area is in flux too; as software gets more sophisticated and printer designs continue to improve, knowing the details may become less important. But for now, it really helps to know how the machine was built and what the likely culprits are when there are problems.

■ **Tip** If you are deciding whether to buy an assembled printer or a kit, note that most manufacturers post assembly instructions online. You can always look at the instructions before you buy and decide whether the assembly is within your skill and time limitations.

3D Printer Design Considerations

In the rest of the book we will talk about parts of the printer, and we will introduce them now with some pictures so that you know what we are talking about later on. A filament-based 3D printer has been called a computerized hot glue gun: basically it takes plastic filament, melts it, and puts it down in layers. There are several key components in this requiring many design tradeoffs among the various options.

Filament

Chapter 7 discusses filament and its handling in great detail. Filament typically comes on spools (for open source printers) or, in some cases, in proprietary cartridges. Printers need to have some means of getting filament off the spool by allowing the filament to turn on a spindle or a lazy-susan-type tray. In some cases, this is part of the frame or attached to it; in other cases, the filament rests on a lazy susan next to the printer.

Frame

As noted earlier in the chapter, the frame of a printer needs to be stiff and sturdy for the prints to build up accurately. If the frame is sloshing around, it is unlikely that you will be able to have an accurate print. Various types of aluminum, extruded rails typically make up frames. Laser-cut or 3D-printed joints typically make up the rest of the frame.

Build Platform

Every 3D printer needs to have a flat surface to build the print. This surface is commonly called *the build platform*, or sometimes just the *platform* or *bed*. Some printers have a heated platform to allow printing of materials that need to be kept warm during building. Others just have a glass or other plate that needs to be covered with tape of some sort to ensure that the first layer of the print will stick.

The printer in Figure 2-1 has a heated platform covered with Kapton high-temperature tape. The one in Figure 2-2 is unheated and covered with blue painter's tape to allow printing of a plastic called PLA (polylactic acid). Chapter 7 details what type of build platform surface is necessary for different filament types.

Extruder Design

The extruder is the part of the printer that melts and moves the filament. The extruder has several parts. One is an extruder drive mechanism, which is a motor and a mechanism that pushes the filament into the hot end. The hot end in turn is comprised of a heater, a nozzle, and a sensor (a thermistor) to sense how hot the bed is. You can see two extruders on the printer in Figure 2-1, which is a dual-extruder machine capable of printing objects out of two materials.

Bowden and Direct-Drive Extruders

There are many different extruder designs, which fall into two major categories. A *direct-drive extruder* (like the one on the machine in Figure 2-1) has a motor and drive gear pushing the filament right next to the hot end. A Bowden extruder (like the one on the machine in Figure 2-2) has a drive gear that is separated from the hot end with a guide tube.

The main reason for using a Bowden extruder is that it moves the heavy motor away from the nozzle, which can make the part of the extruder that is moving a lot lighter. This can allow for faster printing speeds, but at the cost of a more complex extrusion system.

Retraction

When the printer is creating a layer, there are holes and filled areas. Some of the holes can be made by having the nozzle zip around the edge of the hole. Sometimes, though, it is necessary to stop extruding across a gap in the layer. In that case the extruder has to *retract* the filament. The drive gears need to be able to pull filament back as well as push it forward to make this work. How much to retract during a print is something a user can set during the process of slicing a model into layers (discussed in Chapter 5). Retraction has a strong effect on print quality.

Nozzles

The nozzle is one of the most critical pieces of the printer and one of the more delicate ones. The holes are tiny and easily clogged. To a degree, the nozzle material and quality define what materials your printer can safely melt and therefore print. Good-quality nozzles can handle polycarbonate, nylon, and other higher-temperature plastics. The nozzle is part of the hot end, which includes the nozzle, the heater block, the thermal break (barrel), and, in many designs, a heat sink to cool the top part of the thermal break. Some designs depend on the insulating properties of high-temperature plastics or, occasionally, ceramics (at the cost of being able to extrude higher-temperature materials).

Moving Parts

3D printers need to move some combination of the extruder and the build platform to be able to create objects. They achieve this with a combination of stepper motors attached to drive screws or cable, belt, or other systems attached to pulleys.

A stepper motor (Figure 2-4) is a precise, brushless, direct current (DC) motor that moves the shaft in predefined angular steps. Motors for 3D printers typically have 200 steps per revolution. The stepper motor is then coupled to a drive screw (like the *z*-axis motors for the printer in Figure 2-1) or to a belt or cable.