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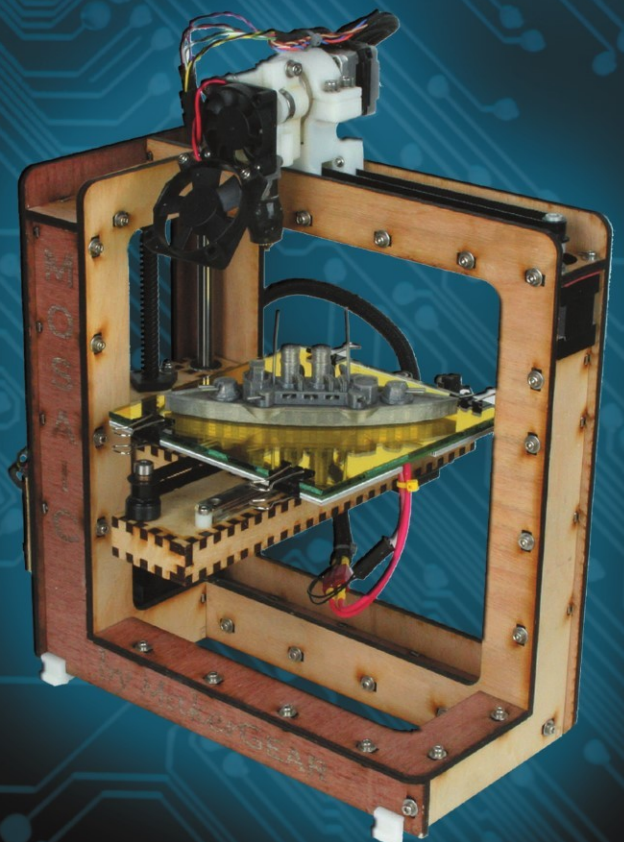

Brian Evans

Practical 3D Printers

Brian Evans

Apress®

Practical 3D Printers

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For my father, who opened his garage and taught me
how to tinker at a very early age

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About the Author

Brian Evans is an artist working in electronic media and Assistant Professor of Art at Metropolitan State University of Denver, where he teaches multidisciplinary courses in art on topics that include electronics and digital fabrication. Many of his classes use open-source hardware—including MakerBot or RepRap 3D printers and the Arduino electronics platform—to create new works in art and design.

He is the author of *Beginning Arduino Programming* (Apress, 2011) and contributed to *Arduino Projects to Save the World* (Apress, 2011) with Emery Premeaux. His work has been shown at the Los Angeles Municipal Art Gallery at Barnsdall Park, the Orange County Center for Contemporary Art, and the University Art Museum at California State University, Long Beach. In 2009, Evans was a resident and contributor to the Grounding Open Source Hardware residency and summit at the Banff New Media Institute in Alberta, Canada, and in 2011 a contributor to the Open Hardware Summit in New York. He received an MFA from California State University, Long Beach in 2008, and a BFA from Arizona State University in 2005.

About the Technical Reviewer

Tony Buser began his technology career in 1995 by writing HTML code. From there, he moved into web site and intranet application development and now works as a web developer for MakerBot Industries in Brooklyn, NY. Tony loves turning virtual digital information into physical reality, and he believes that the affordable and easy-to-use 3D printing and personal fabrication technology might very well be the most significant new technology since the World Wide Web. He is excited to be a part of its development at such an early stage and can typically be found spending untold hours in his basement workshop in Reading, PA with his four 3D printers: two Makerbots, a RepRap, and a whiteAnt. And he's always building more.

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Finally I want to acknowledge the vast multitude of talented artists, designers, engineers, tinkerers, and makers everywhere that have created such a rich and diverse 3D printing community for which this book extensively draws from. While too numerous to name everyone here, I would like to thank each and every one of you that generously contributed directly to this book by sharing images of the things you have made, or indirectly by advancing some truly great ideas and engineering genius. Thank you all.

Introduction

Wired, *The New York Times*, *The Economist*, *The Wall Street Journal*, BBC, and even *The Colbert Report*, yes—personal 3D printing is everywhere. 3D printing, sometimes called *additive manufacturing* or *rapid prototyping*, is all about building 3D objects using plastic and other materials from a digital design. As a technology, it has actually been around and in use by engineers and designers for more than 25 years. It hasn't been until the last five years, though, that *personal* 3D printing has begun to make such an impact—where objects made on a machine that might cost $30,000 in the industry can now be made with nearly the same quality on a machine that fits at home on your desk for less than $2,000.

Better yet, it doesn't take a trained designer or engineer to design and print 3D objects on this new breed of personal 3D printers. In fact, these machines are actively used throughout K–12 education right now, and the technology is becoming increasingly more popular every year. All it takes is an insatiable curiosity about things, the desire to tinker and experiment, and a willingness to learn a handful of different applications that can be used to design and print 3D objects. The things people make with their 3D printer range from as simple and practical as a clothespin to as ridiculous and wonderful as an entire robotic petting zoo.

This book assumes that you are as deeply inspired by the idea of personal 3D manufacturing as I am. Maybe you are just now considering buying your own 3D printer to see what it's all about. Or maybe you have already bought your first 3D printer and are now trying to figure out what exactly to do with it. Either way, this book will be your guide as you learn the ins and outs of both your 3D printer and how to design objects to be made with it.

Why Own a 3D Printer?

Why own a 3D printer? Because it's fun! While many might rave about the economic benefits of owning a 3D printer or the way in which personal 3D printing will revolutionize our world, these viewpoints are all just a bit too hyperbolic for me—and miss the fundamental point. Sure, you might be able to make a few dollars printing things and selling them on sites like Etsy or Ebay. And sure, once you have a 3D printer, you start to look at things around the house a little bit differently. Above all else, though, you should want to own a 3D printer and learn how to use it because it can really be a lot of fun. My students and I spend countless hours watching things emerge from our 3D printer—it's amazingly mesmerizing.

You might be a designer looking to integrate this technology into your professional practice. Or an artist exploring the realms of a relatively new media. Maybe you're an inventor and need your own desktop assembly line. On the other hand, maybe you want to explore the possibility of creating 3D printed jewelry. Or you happen to like trains. Or robots. Whatever you're into, above all you should probably enjoy the simple act of tinkering. If you are buying your very own personal 3D printer, then I can assure you it will not "just work" like the document printer that you most likely already own. It's just not that simple, and that should be considered a good thing. It might be challenging at times to make your 3D printer do exactly what you want of it, but that is a big part of the fun.

It's a Big World of 3D Printers

In the last five years, we have gone from a single personal 3D printer to hundreds of them. From RepRaps to MakerBots; Printrbots to Mosaics. There's a bunch of them out there and every week it seems there is a brand-new 3D printer that someone has designed and is putting out into the world. So how can one single book

encompass all of these 3D printers? In some ways, it can't. There are just too many personal 3D printers out there and simply no way to cover them all in sufficient detail.

Although we can talk about all the ways these many different printers are alike. We can also look at how to use 3D printers in general and how to design objects to be printed on them. We will discuss specifically a handful of different 3D printers, and the software and electronics that make them work. We might have missed your favorite printer, but it's a big world out there and the best thing we can do is build on what the printers have in common to get you started with 3D printing the right way.

Find a 3D printer that makes you happy, and let's figure out how to use it.

About This Book

This book is roughly divided into three sections: hardware, software, and upgrades. The first three chapters cover the hardware side of things by starting with the big picture of how 3D printers work and digging down to the specifics of a 3D printer's toolchain, before wrapping up with some useful tips for making your first 3D prints and calibrating your machine. The largest part of this book covers all the different sorts of software that can be used to design and print 3D objects, with projects that include a diverse range of topics— from 3D text, multipart models, robotics, and 3D memes. We wrap up the book with some helpful upgrades and resources for working with and improving your 3D printer.

This book is designed both as a how-to manual and as a reference. As a manual, starting with Chapter 1 and working all the way to the end, we walk through the process of buying a 3D printer, learning how it works, calibrating the printer, designing objects for printing, and then ending with how to improve the printer after we've given it a good run. If you already have a little knowledge of 3D printing or design, then this book provides a useful reference to support those things that you might want to learn more about. This might include designing shapes in an illustration application and then extruding it into three-dimensions, learning more about parametric computer-aided design (CAD), or even how to process and prepare 3D models for printing.

This book is not an instruction booklet for how to build a Model X 3D printer. If we were to do that, then the book would be obsolete before it were published. Even as I write this now that the book is finished, a few changes in the available models of 3D printers are already underway. Instead, we will assume that once you make your 3D printer purchase you'll be able to figure out how to put it together and get started. We will pick up again at that point, guiding you along the way of breaking in the new printer and making new things with it. The 3D printer enthusiasts are an amazingly active community of makers who go out of their way to share information with the world. Rely on the many forums, wikis, blogs, and other sources of online knowledge to get your 3D printer up and running—many of these resources are listed at the back of this book in Appendix B.

Our design projects in Chapters 4 through 9 take a thematic approach to our project considerations and the type of software used in their creation. The intent is that these projects will give you a broad range of real-world, dare we say practical applications for designing and building 3D objects with your new 3D printer. We will introduce a handful of software applications this way, which can be used in various capacities to model 3D objects. There is not "The One" 3D application that can do everything that we might want, and that diversity makes things interesting. Every reader will have their own personal style and what works best, or doesn't, for them. If I did my job right, then this book should have a little something for everyone.

Learning by Making

The best lesson I can give to my students is that you learn best by making something. The projects in this book might at first seem, at least to a few, limited to some way-out-there or even goofy ideas, but everything we make in this book should be directly applicable to many of the things you would want to make every day if you only knew how. You are really only limited by your own imagination. But first, start with these projects, give them a try, tinker with them to see what happens, and use them as a jumping off point for your own creations.

Not only do you learn by making, but making mistakes is also a very important part of the process. This is called *iterative design*: make one thing, see what works and what doesn't, make a new version, see how it can be

improved, and make another new version. Iteration and experimentation are ways to learn those types of things that we can't really teach you in this book. How does the material hold up to repeated stress, to sunlight, or to water? What does it feel like and how quickly will it wear out? By having your very own desktop factory (well, almost), you have the power to make an infinite number of iterations to improve your designs and share those with the world.

Sharing Things

Sharing things is a very important aspect of this whole 3D printing community. All of the designs in this book are licensed under a Creative Commons Attribution-ShareAlike license (`www.creativecommons.org/licenses/by-sa/3.0`). Each design can be easily downloaded from the thing-sharing site, Thingiverse (`www.thingiverse.com`), by searching for my user profile, `bwevans`, or for the tag `Practical 3D Printers`. My hope is that everyone who picks up this book will make many, if not all, of the projects and create even more new designs from the lessons learned here.

I desperately want to see each and every one of them, so if you make something from this book, be sure to use the I Made One button from that project's page on Thingiverse, discussed in Chapters 3 and 4, and post a photo of your thing. If you make a new derivative or something inspired by this book, then be sure to either post your thing on Thingiverse as a derivative of the project or use the `Practical 3D Printers` tag so that others can find it, including me. Hopefully, I will come to know everyone that reads this book through the things that you make.

CHAPTER 1

A World of 3D Printers

If you've picked up this book, then you are as captivated by the possibilities of 3D printing as much as I am. Maybe you've seen one of the many personal 3D printers in the media and you want to know more; maybe you are an artist, designer, engineer, inventor, or a maker of things and want to know how to get started 3D printing your designs; or maybe you have already purchased your 3D printer and now just need some help in learning what to do with it. This chapter begins our journey with 3D printers, starting with a general overview of how 3D printers work. We then take a look at many of the current DIY 3D printers on the market today for under $2,000 to serve as a buyer's guide for picking up a new printer, or simply just to give you an idea for where the 3D printer you might already own fits in. We will then wrap up the chapter with a discussion of the materials and supplies that you will need to successfully complete the projects in this book.

In this chapter, we will do the following:

- Find out what a personal 3D printer is and how it works
- Survey many of the different types of DIY 3D printers available today
- Review the different materials that are available to print objects with
- Discuss the various tools and supplies needed to successfully make 3D prints

Let's begin by trying to separate the science fiction of 3D printing from the reality of making objects with a 3D printer.

Tea. Earl Grey. Hot.

These words should sound familiar to many of you. The character Captain Jean-Luc Piccard from TV's *Star Trek: The Next Generation* would say these words to a terminal in the wall and his beverage of choice would materialize in front of him within mere seconds. This fictional device was called a "replicator," a machine that reorganized the atoms of basic materials to create all manner of new things at the instant of a request. Just to be clear with the current state of 3D printers: we are not there yet. The advances that a community of industrious developers have heralded into place over the last few years has been nothing but astonishing; however, we are a long way from reforming molecular structures to make things from thin air.

Instead, the personal 3D printers of today most often build things from plastic using a process called fused filament fabrication (FFF). Plastic filament is heated and extruded from a nozzle like a tiny and precise hot glue gun while the machine draws out 3D objects layer by layer. As one layer of plastic is laid on top of another, they fuse together, and, when cooled, form a solid and durable plastic part. This technology has been around for about 25 years and used in the design and engineering industries for everything from designing parts for cars to designing toaster ovens.

Because today's industrial printers cost in the tens to hundreds of thousands of dollars to start, a few brave souls dared to ask that fateful question, "How hard could it be to build our own 3D printer?" The answer, at

least initially, was something along the lines of very hard; however, over the last five years (since the first DIY 3D printer was assembled), many advances in the technology have been made through the combined efforts of developers that have made the many thousands of 3D printers worldwide. To see the ever-evolving taxonomy of 3D printers, be sure to visit the RepRap Family Tree at `http://reprap.org/wiki/RepRap_Family_Tree`. For now, let's take a broader look at how these printers work.

How a 3D Printer Works

All of the personal 3D printers that we will look at in this chapter share many similarities with one another, at least in principle, although they might each approach things a little differently. Let's take a closer look at how these 3D printers work using the example shown in Figure 1-1.

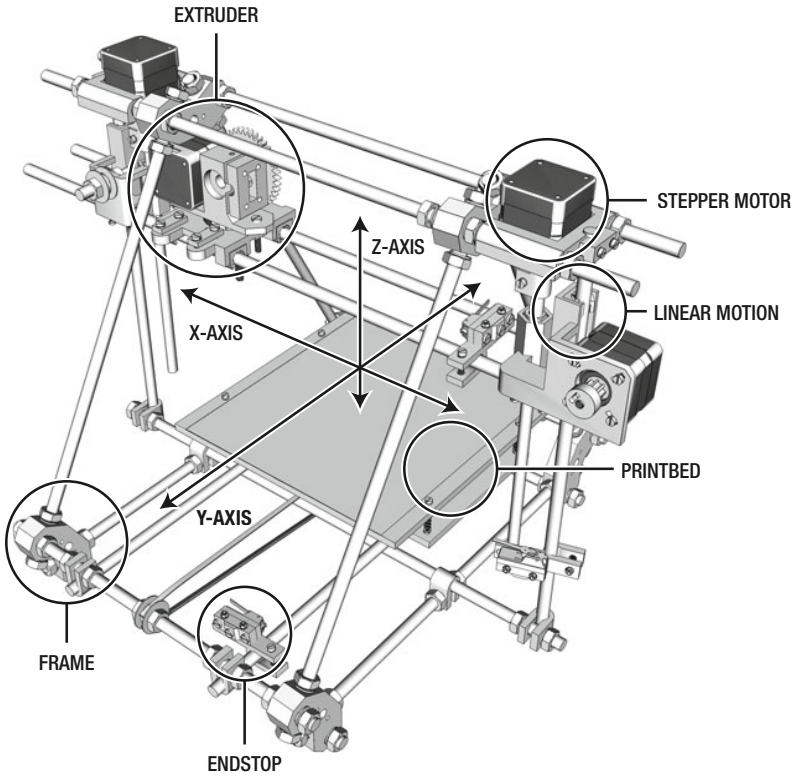

Figure 1-1. *How a 3D printer works (original model courtesy Gary Hodgson, 2011)*

Cartesian Robot

Central to a 3D printer is the idea of a Cartesian robot. This is a machine that can move in three linear directions, along the x-, y-, and z-axes, also known as the Cartesian coordinates. To do this, these 3D printers use small stepper motors that can move with great precision and accuracy—usually 1.8 degrees per step, which translates to resolutions in the fractions of a millimeter range through the unique way that these stepper motors are controlled. The three-axis robot is like any other computer numerically controlled (CNC) robot and is able to position its

thermoplastic extruder along each of these linear axes of movement to lay down layer upon layer of hot plastic. All of the 3D printers in the book use timing belts and pulleys along their x- and y-axes to provide fast yet accurate positioning, and most use threaded rod, or lead screws, to position the z-axis with even greater precision.

While it might all sound complex, it is really not all that complicated, as nearly all of these DIY 3D printers use standardized off-the-shelf components that are put to use in many different industries. In part, it took a lot of hard work over the years to figure out what worked well and what didn't to end up with such outstanding printers today. Thanks to an open and sharing community, these designs and improvements have been shared freely, further improving the technology.

Thermoplastic Extruder

With our Cartesian system providing accurate linear positioning, we need an extruder capable of laying down thin strands of thermoplastic—a type of plastic that will soften to a semiliquid state when heated. The extruder (see Figure 1-2), arguably the most complex part of a 3D printer that is still seeing intense development, is actually the marriage of two key elements: the filament drive and the thermal hot end.

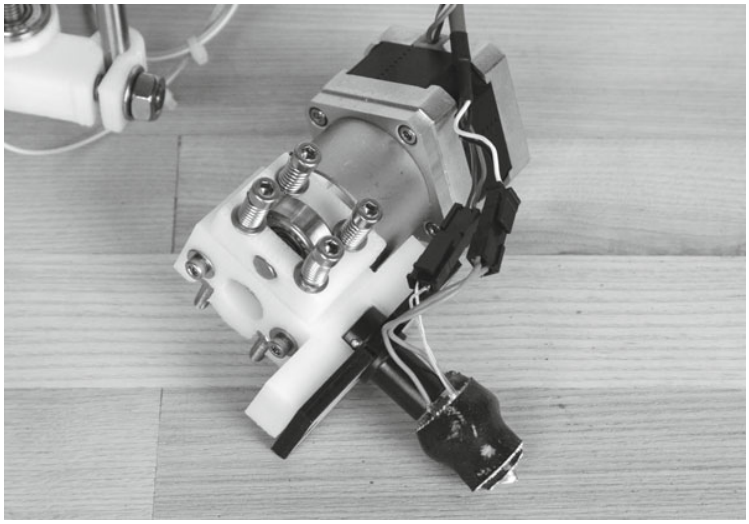

Figure 1-2. *Complete extruder with filament driver and hot end*

The filament drive pulls in plastic filament often bundled in spools of either 3mm or 1.75mm diameter filament using a geared driver mechanism. Most, if not all, contemporary filament drivers use a stepper motor to better control the flow of plastic into the hot end. These motors are often geared down with printed gears or an integral gearbox, as shown in Figure 1-2, to give the filament driver the strength needed for continued extrusion.

The filament, after being pulled into the extruder by the filament driver, is then fed to the heater chamber or hot end. The hot end usually is thermally insulated from the rest of the extruder and is made up of either a large block of aluminum with an embedded heater or some other heater core, along with a temperature sensor. When the plastic reaches the hot end, it is heated to somewhere around 170°C to 220°C, depending on the plastic to be extruded. Once in a semiliquid state, the plastic is forced through a print nozzle—with an opening somewhere in the vicinity of 0.35 millimeters to 0.5 millimeters in diameter—before laying this thin hot extrusion onto the printbed drawing lines that outline that layer of the shape to be printed or fill that layer using some type of infill pattern.

Printbed

The printbed is the surface that your 3D prints are built on. The size of a printer's printbed will vary from one printer to the next, ranging from 100mm² to 200mm², somewhere between 4 inches and 8 inches or larger. Most, although not all, personal 3D printers on the market offer a heated printbed (see Figure 1-3), either as standard or as an option, although it is also easy to build one from scratch if needed. The printbed is used to prevent warping or cracking of prints as they cool and to create better adhesion between the first layers of the print and the printbed surface.

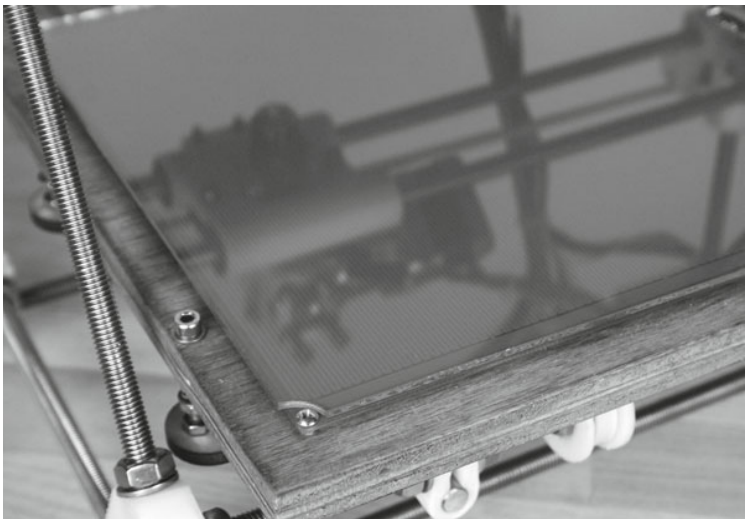

Figure 1-3. *Heated printbed*

The surface of the printbed is often made from either glass or aluminum to better spread the heat across the area and to make for a smooth and level surface. Glass provides the smoothest surface to print on while aluminum conducts heat better for a heated platform. To prevent the object from lifting off the surface in mid-print, these surfaces are often covered in one kind of tape or another to provide a surface that is inexpensive to replace periodically. These materials include Kapton or polyimide tape, PET or polyester silicon tape, or even hardware store–variety blue painter's tape, depending on the type of filament used.

Linear Motion

The type of linear motion system (or the mechanical assembly that allows each axis to move) that is used by the 3D printer will often determine how accurate the printer is, how fast the printer can print, and how much or how little maintenance will be needed by the printer over the long term. Most personal 3D printers use smooth, precision ground rods for each axis, and either plastic, bronze, or linear ball bearings to glide across each rod. Linear ball bearing systems have gained a lot of popularity lately for their longevity and smoother operation over the life of the printer; although they are often louder during operation than bronze bushings like the self-aligning variety shown in Figure 1-4, which are generally quieter but often require a little more work to align during the build process.

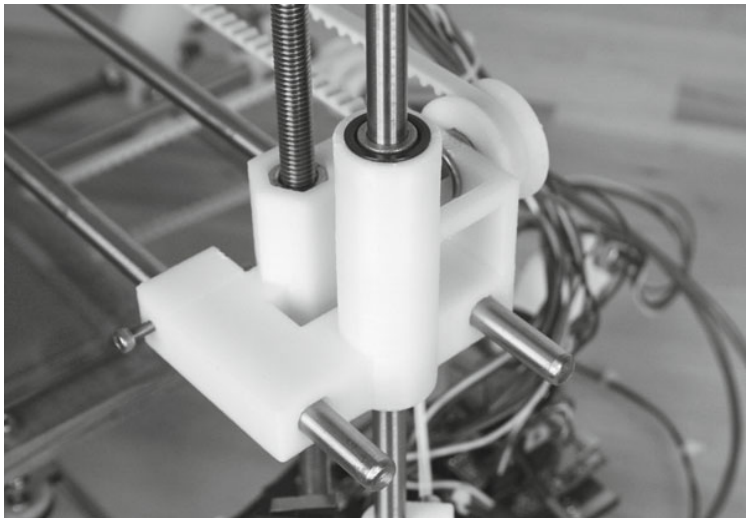

Figure 1-4. *Self-aligning bronze bearings on a Prusa Mendel*

The "best" type of linear motion system for a 3D printer is about as personal a decision as the kind of car you drive. 3D printed bushings are very cheap, but don't last that long. Machined plastic bushings (called Igus bushings) are very smooth and work well for the slow-moving z-axis, but they tend to deform under heavier use. On the other hand, the reliability of linear bearings discussed earlier depends on the quality of the smooth rails they ride on and they cost more. Other, more exotic materials, like felt, have also been tried with mixed results. Some printers even use industrial linear glides that have the potential for greater accuracy and longevity at increased cost and mechanical complexity.

Endstops

The length of travel for each linear axis is limited by usually mechanical or optical endstops (see Figure 1-5). Basically, these are switches that tell the printer's controller electronics when it has reached a limit in one direction of movement in order to prevent the axis from moving past its limits.

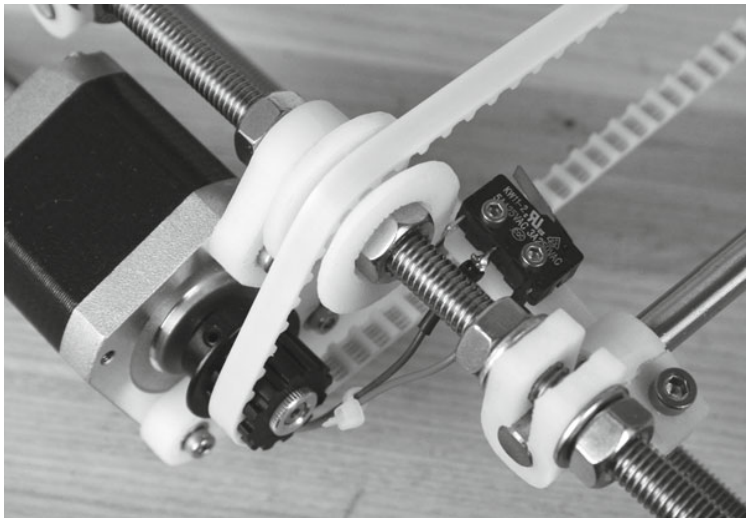

Figure 1-5. *Mechanical endstop on y-axis*

While endstops are not strictly needed for operation, having at the very least one endstop in the minimum position on each axis will allow the printer to home itself at the beginning of each print for repeatable and accurate prints every time. We will discuss the electronics in greater detail in Chapter 2.

Frame

Holding everything together is the 3D printer's frame. This frame forms the structural element of your 3D printer and its material and construction determine a lot about the final accuracy of your printer. All of the RepRap style designs will use 3D-printed components along with threaded rod and other hardware to make the frame structure. On the other hand, Box Bots like the MakerBot or the MakerGear Mosaic use laser-cut plywood that is bolted together to make the frame, as shown in Figure 1-6.

Figure 1-6. *MakerGear Mosaic plywood frame*

A laser-cut plywood frame uses slot-and-tab construction, where two pieces of plywood are held together with tabs from one piece fitting into slots in the other, and connected with nuts and bolts. This type of frame is generally easier to assemble and offers better up-front precision so that printer calibration is easier; however, these frames are often louder during operation and all those screws will eventually need retightening later. Conversely, threaded rod frames make for quieter robots, but add to an even more complex assembly and calibration. If you are sourcing all the parts for your 3D printer, then you will often need to cut the various lengths of threaded and smooth rod again, adding to the complexity of the overall build. Finally, some of the more recent printer designs are using commercial aluminum extrusions to build a frame that is rigid and easy to assemble, although it can cost as much as $100 to $200 more.

So that's a brief overview of the main components in a 3D printer. We will look at the workflow of moving from a digital 3D model to printing a 3D design in the next couple of chapters; but for now let's talk about some of the more popular and affordable 3D printers on the market today and how they compare with one another.

A Survey of 3D Printers

There is a diverse and rapidly expanding field of 3D printers—so big, in fact, that to give all of the available printers ample coverage, it would take a book just on that alone. We can't cover everything here, but what we can do is to provide a brief survey of some of the most popular printers available right now. These printers can be roughly categorized into four main groups: the RepRaps, the Box Bots, RepStraps, and the Upstarts. All of the printers discussed here can be purchased for $2,000 or less in a kit form or sourced from individual parts and suppliers. Each of these 3D printer designs has been proven through extensive testing and development, and if available through a retailer, the company has proven to be reliable and consistent. If you choose to build a 3D printer yourself instead of buying a preassembled one, you will find that it is generally not that much more difficult than building your own personal computer—although being handy with the business end of a wrench is helpful.

RepRaps

The RepRap, developed by Dr. Adrian Bowyer at Bath University, is the 3D printer that started it all in 2007. The first RepRap (short for "replicating rapid-prototyper") named Darwin, was a 3D printer capable (at least in theory) of reproducing itself by printing the parts needed to make a new one. By designing a working 3D printer using 3D printed parts (albeit parts printed on an expensive industrial machine in the beginning) along with off-the-shelf hardware, the RepRap broke through the price barrier of industrial 3D printers. With the Darwin, RepRap started the DIY 3D printer revolution that has been evolving ever since.

RepRap Mendel

Darwin was eventually replaced by a second-generation RepRap named Mendel, which was further refined in 2010 by Josef Prusa to require fewer parts, both printed and hardware, while retaining most of the functionality. This new stripped-down design has been called the Model T of 3D printers and for good reason: it operates under the mantra of function over form and it can be very affordable. One of the highest quality Prusa Mendel kits available on the market today, shown in Figure 1-7, is produced by the Ohio-based company MakerGear (`www.makergear.com`).

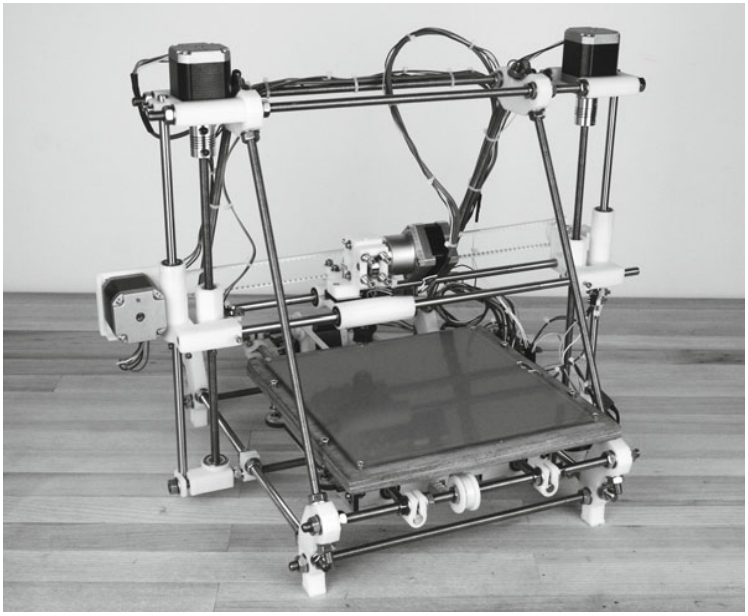

Figure 1-7. *MakerGear Prusa Mendel*

The Prusa Mendel is a low-cost, low part-count 3D printer that has a useable build volume of 200mm × 200mm × 110mm (roughly 8" × 8" × 4.5") with a frame built using a combination of printed parts, threaded rod, and other hardware. Prusa Mendels use two motors for the z-axis wired in parallel to reduce the amount of manufactured parts like pulleys and timing belts. MakerGear improves on the basic design by using stainless-steel hardware, self-aligning bronze bushings for linear motion, a heated printbed, and a laser-cut sled for the y-axis.

If you are more interested in saving a few pennies than getting all the bells and whistles, the Prusa Mendel can be one of the least expensive printers to obtain—if you source all of your own hardware and have a friend or hackerspace nearby that can print the plastic components for you. For more information, head over to the

RepRap wiki at `http://reprap.org`. These printers take significantly more time than others to build and get properly calibrated, especially if you are sourcing all of your own parts; however, there is a large group of Prusa Mendel owners that are willing to share their knowledge, advice, and improvements for the design.

The following are some of the highlights of the Prusa Mendel:

- Mid-range build volume
- With some work, can obtain quick print speeds
- Very affordable if sourcing your own parts
- Takes quite a lot of time to build and properly dial in

RepRap Huxley

The Huxley design is the smaller, more portable brother of the RepRap Mendel. Currently, the Huxley design of choice, shown in Figure 1-8, is made by RepRapPro, Ltd. (`http://reprappro.com`), lead by RepRap's primogenitor, Dr. Adrian Bowyer, and eMAKER's Jean-Marc Giacalone.

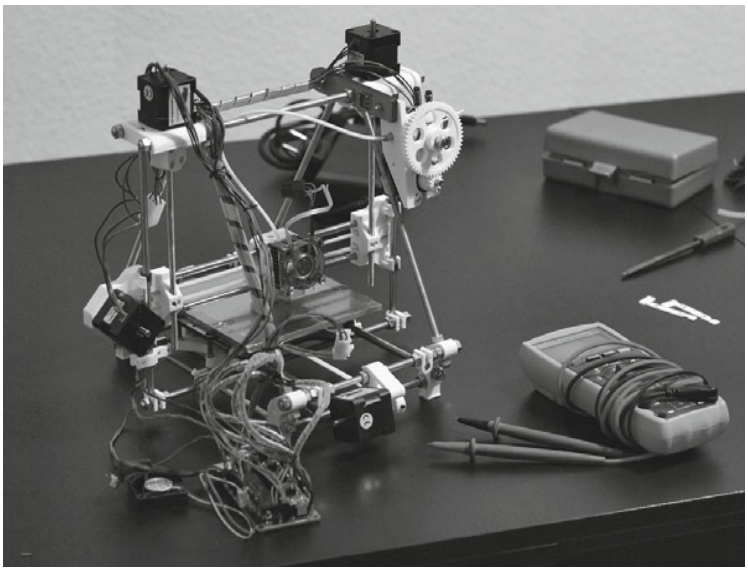

Figure 1-8. *eMAKER Huxley (courtesy Johannes Heberlein, 2011)*

The Huxley is a little cheaper than the Prusa Mendel, depending on whether you source it yourself or if you buy a kit, although size and portability is more important to this design than price. The Huxley features a modest, build volume of 140mm × 140mm × 110mm (about 5.5" × 5.5" × 4.5")—in one of the smallest 3D printers in overall size. Through a combination of linear bearings on the x- and y-axes and fine pitch threaded rod on the z-axis, the Huxley is capable of some astonishingly detailed prints.

Because of the smaller size of the printer, the filament driver portion of the extruder that normally rides on the x-axis carriage has to be separated from the hot end and relocated to the frame of the printer. To link the filament driver and the hot end, the designers use something called a Bowden cable, basically a plastic tube that connects the filament driver to the smaller hot end on the x-axis carriage. This can be seen as a good or bad thing, depending on your point of view. Either this design offloads much of the bulk of the extruder from the x-axis,

allowing it to move more quickly and with greater accuracy, or it might present problems with the actual plastic extrusion because of the added complexity of this arrangement and the increased friction of the tube, causing prints that look stringy in appearance.

The following are some of the highlights of the RepRap Huxley:

- One of the smallest available printers with a modest build volume
- More accurate and reliable linear motion system
- Bowden cable extruder is either a pro or con
- Takes almost as long to build and set up as a Prusa Mendel

Box Bots

Where the RepRaps are unified by their basic design premise and a loose affiliation with the `reprap.org` web site, Box Bots can only be easily grouped together because of their use of plywood frames, built from bolted-together, precision, laser-cut panels. Because of this, and unlike the RepRap printers, a 3D printer is not needed to produce one of these kits, making them easier and faster to distribute. Additionally, the printer's assembly is often much easier than the RepRaps', making the printer more precise and easier to calibrate. This section looks at three different printers made by three different companies that are attempting to make 3D printers for the masses.

MakerBot

MakerBot Industries (`http://store.makerbot.com`) was the first post-RepRap 3D printer to introduce an easy-to-assemble, low-cost 3D printer kit with their Cupcake CNC in 2009, which, while inspired by the RepRap Darwin, used a laser-cut plywood frame and structural components along with off-the-shelf hardware. MakerBot's second-generation Thing-O-Matic, shown in Figure 1-9, featured numerous advancements in their linear motion control and extruder technology.

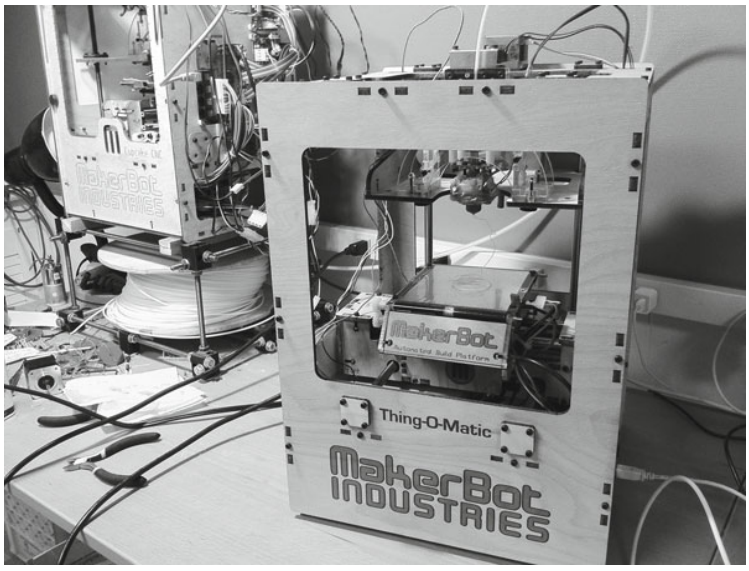

Figure 1-9. *MakerBot Thing-O-Matic (foreground, courtesy Tony Buser, 2011)*