

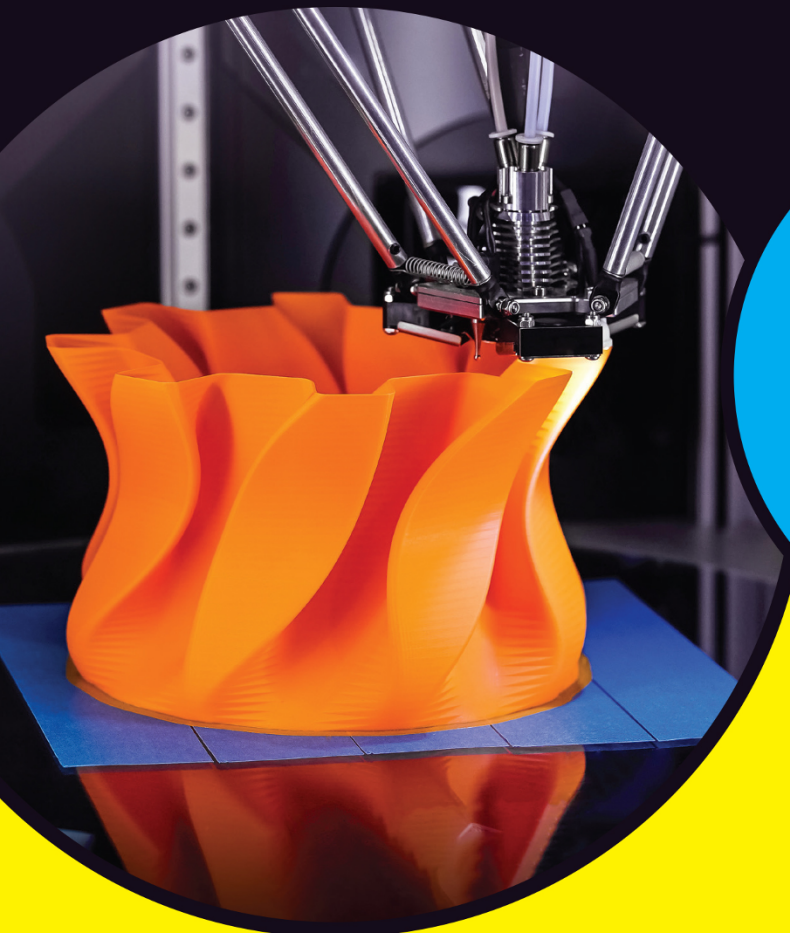
LEARNING MADE EASY



3rd Edition

3D Printing

for
dummies[®]
A Wiley Brand



Design for the
3D printing process

—
Explore practical
3D printing

—
Learn how 3D printing
can work for you

Richard Horne



3D Printing

3rd Edition

by Richard Horne

for
dummies[®]
A Wiley Brand

3D Printing For Dummies®, 3rd Edition

Published by: **John Wiley & Sons, Inc.**, 111 River Street, Hoboken, NJ 07030-5774, www.wiley.com

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Published simultaneously in Canada

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Library of Congress Control Number: 2023943991

ISBN: 978-1-394-16947-4 (pbk); 978-1-394-16948-1 (ebk); 978-1-394-16949-8 (ebk)

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Introduction

3D printing has been around for more than 30 years, but for much of that time it would have been inconceivable for anyone without corporate backing to even think of taking advantage of this technology. Recently, however, the core technology for 3D printers has developed to the point where it is now available at prices many individuals and smaller companies can afford.

Three key things make 3D printing stand out from almost any other manufacturing process:

- » **Printed parts are “grown” in layers.** Many complex objects that have internal structures or are comprised of interlocking sub-assemblies can be manufactured in a single run, with no further intervention, whereas previously they would be made from many separate parts, some of which could not be made by fully automated machining processes or more traditional means. Multiple materials can be used together to improve the performance or overall integration of the finished part. For example a simple referee’s whistle needs to have a hollow inside with a slot and pea inserted that will not fall out. All traditional methods for manual or automated manufacture would require at least three separate parts to be connected together. With 3D printing, the hollow shell of the whistle can be made as a seamless object and the pea inside can be printed and designed to release and form the rattle all in a single operation where the finished whistle is ready to use directly after 3D printing.
- » **Material is added rather than subtracted.** This method of manufacturing adds raw materials to build an object rather than removing material. Machining away 90 percent of a metal block to make a cooling system for a race car is far less efficient than adding the 10 percent or so of metal powder needed to make a more compact and efficient design that couldn’t have been machined in the first place.
- » **3D printing often eliminates the need for complex or expensive production tooling.** This benefit is becoming significant as 3D printers are being used for mass manufacturing runs in which individual tooling or hand-crafting would make customized products far too expensive (such as solid gold jewelry).

In short, 3D printing turns a digital model in a computer data file into a physical representation of the object or product. The term *3D printing* is now widely used by media and communities to help communicate the idea that an object is being produced in a similar way as a paper printer, but as a physical three-dimensional

part. The term 3D printing is often disliked in the wider industry, as it's a poor representation of what this technology can achieve. A more professional name is *additive manufacturing*, which covers a vast array of sectors, materials, and processes used to produce physical objects from data.

Since the first edition of this book was released in 2013, desktop 3D printing and various forms of industrial additive manufacturing have been through the rise and fall of a technology hype cycle. Reports about 3D printing applied to biomedical research anticipated the leap from lab to patient too soon, rather than focusing on the possibility of printing tissue samples for medical research. Researchers and individuals are still working out appropriate uses of 3D-printing technology. Often, they come to the conclusion that there are still vastly better ways to produce many things without 3D printing.

Much of the media hype surrounding 3D printing was exactly that: hype. But we are now approaching the end of that hype cycle, and 3D printing is stronger than ever. Most 3D-printing equipment vendors realize that not everyone needs or wants a home 3D printer. The desktop 3D-printing market has returned its focus to people who need and want to explore this technology.

About This Book

3D Printing For Dummies, 3rd Edition, was written with the average reader in mind. It's a survey of the existing capabilities of additive manufacturing for both private and commercial purposes and a consideration of the possibilities of its future.

In this book, I review many current additive manufacturing technologies. Some are early uses of a technology or process with numerous limitations and caveats regarding their use. I also explore what types of desktop machines are available to buy and use straight away while also looking at those kits that require some assembly on the user's part. I dive into the software you will need (often as freely available open-source downloads) and then look at the tips and tricks needed to design for the 3D-printing process. This book won't make you an expert in all aspects of 3D printing, but it will give you a good overall starting point for learning the art of 3D printing and an opportunity to explore additive manufacturing systems. I hope that you'll be excited by the amazing potential of 3D printers — excited enough to buy your own desktop machine and learn how to design and make useful, practical, and fun objects for you to use and share.

Every time this book has been updated, it's always wonderful to see many of the things discussed as early concept ideas and research turned into realities, now being used in everyday life. 3D printing is truly changing the way we design and make products as individuals and extensively in wider world industries. It's a technology that's already touched your life even if you haven't realized it yet.

Foolish Assumptions

You may find it difficult to believe that I've assumed anything about you; after all, I haven't even met you! Although most assumptions are indeed foolish, I made these assumptions to provide a starting point for this book.

- » You have the ability to download or access programs in a web browser if you want to try some of the applications I review in this book. (It also helps to have an open mind and enthusiasm about the future and what additive manufacturing can produce.)
- » If you want to buy and use a desktop 3D printer of your own, you need to be familiar with using hand tools like spanners and screwdrivers. We are still at the point where regular maintenance, servicing, and changing consumable items are a part of owning a 3D printer. You will also need a computer and software, much of which is free to download and use.
- » You do not need any experience with 3D design. However, it helps to have a basic understanding of how a 3D model is just like any other digital model; we're just using that digital data to reproduce physical objects.
- » It is important to understand that the current level of sophistication of 3D printers is close to the first dot-matrix paper printers. They're slow, and most are still limited to a single material; many offer only a single color or one type of plastic type at a time. Just as the evolution of dot-matrix printers led to inkjet and laser technologies that added speed and full color to paper printers, 3D printers are adding capabilities quickly. But please don't assume that all 3D printers will follow the same rapid adoption of full color and astonishing print speeds that 2D printers experienced in the past. That would be foolish indeed. We are still working with physically melting or solidifying resin materials and not at an atomic level of manufacturing.
- » I try to use two common terms for separating a 3D printer you could use at home (desktop 3D printing) and many of the vastly more complicated and expensive machines used by industry (industrial 3D printers). The main difference between the two types, apart from the cost, is that industrial 3D printers tend to be able to use more robust materials such as metal and produce a higher level of detail, accuracy, or repeatability in the finished parts.
- » I also don't expect you to know all about product design or the fundamental properties of materials. Where possible, I'll try to explain the most common materials used by both desktop and industrial 3D printers.
- » Working with 3D printers is very rewarding, but you should learn how to adjust and tune your own desktop 3D printer. 3D printers are all different, so when things go awry you will be able to fix the issues yourself. It is not necessary to be a do-it-yourself handyman. However, a certain familiarity with basic tools and methods will help you to use your 3D printer, whether you assemble it yourself or buy a fully built and tested machine.

Icons Used in This Book

As you read this book, you'll see icons in the margins that indicate material of interest (or not, as the case may be). This section briefly describes each icon in this book.



TIP

Tips are nice because they help you save time or perform some task without a lot of extra work. The tips in this book give you timesaving techniques or pointers to resources that you should check out to get the maximum benefit from 3D printing.



REMEMBER

Remember icons mark the information that's especially important to know. To extract the most important information in each chapter, just skim these icons.



TECHNICAL
STUFF

The Technical Stuff icon marks information of a highly technical nature that you can normally skip.



WARNING

The Warning icon tells you to watch out! It marks important information that may save you headaches or keep you and your equipment from harm.

Beyond the Book

In addition to what you're reading right now, this product comes with a free access-anywhere Cheat Sheet that covers the basics of 3D printing. There I've listed various 3D printers, control electronics, and aspects about the assembly of a RepRap 3D printer of your own. I also include common terms you'd come across in the software used in 3D printing and the definitions of common settings used by the model-processing software. This should all help you familiarize yourself with 3D printing as you journey through the book. To get this Cheat Sheet, simply go to www.dummies.com/ and type **3D Printing For Dummies Cheat Sheet** in the search box.

Where to Go from Here

The goal of this book is to get you thinking about 3D printing and the potential it offers in your own life, home, or work. We stand at the start of a new form of creative design and product creation, in which traditional mass manufacturing will give way to personalized, individualized, ecologically friendly, on-demand manufacturing close to home — or in the home. You don't have to read this book cover to cover, although you should find interesting and amazing items on each page. In any event, I hope that you take away dozens of ideas for new products and improvements to old ones made possible by 3D printers.

1 Getting Started with 3D Printing

IN THIS PART . . .

Explore the world of 3D printing, including many of the different types of additive manufacturing and their applications.

Discover current uses for the ever-growing spectrum of 3D-printing capabilities available today.

Examine options currently in existence for 3D printing.

Discover ways that you may be able to use additive manufacturing in personal and professional settings.

- » Getting to know additive manufacturing
- » Discovering applications for 3D printing
- » Introducing RepRap

Chapter **1**

Seeing How 3D Printers Fit into Modern Manufacturing

An amazing transformation is currently under way in manufacturing, across nearly all types of products — a transformation that promises that the future can be a sustainable and personally customized environment. In this fast-approaching future, everything we need — from consumer and industrial products to food production and even our bodies themselves — can be replaced or reconstructed rapidly and with very minimal waste. This transformation in manufacturing is not the slow change of progress from one generation of iPhone to the next. Instead, it's a true revolution, mirroring the changes that introduced the Industrial Age and then brought light and electricity to our homes and businesses. This *third Industrial Revolution* is all part of a much wider change in fully automated and intelligent-assisted global manufacturing, linking into what's now being called “the circular economy” or “Industry 4.0.”



TIP

For a great introduction to what these terms *circular economy* and *Industry 4.0* actually mean, take a look at *Industry 4.0 and Circular Economy: Towards a Wasteless Future or a Wasteful Planet?* by Antonis Mavropoulos and Anders Waage Nilsen (also published by John Wiley & Sons).

New forms of manufacturing will give rise to new industries and allow for more efficient use of our dwindling natural resources. Like any truly fundamental change that spans all aspects of the global economy, the change will, by its very nature, be highly disruptive. But traditional, inefficient ways of producing new models of products have already given way to automated processes and precision-controlled equipment that was hard to imagine decades ago. The new technology behind this transformation is referred to as *additive manufacturing*, *3D printing*, or *rapid prototyping*. Whatever you call this technology, in future decades, it will be used to construct everything from houses to jet engines, airplanes, food, and even replacement tissues and organs made from your own cells! Every day, new applications of 3D printing are being discovered and developed all over the world. Even in space, NASA is testing designs that will function in zero gravity and support human exploration of other planets, such as Mars. Hold on tight, because in the chapters ahead, we cover a lot of incredible, fantastic new technologies — and before the end, I show you how you can assemble, test, and run your own desktop 3D printer.

Embracing Additive Manufacturing

What is additive manufacturing? It's a little like the replicators in the *Star Trek* universe, which allow the captain to order “tea, Earl Grey, hot” and see a cup filled with liquid appear fully formed and ready for consumption. We're not quite to that level yet, but today's 3D printers perform additive manufacturing by taking a 3D model of an object stored in a computer, translating it into a series of very thin layers, and then building the object one layer at a time, stacking material until the object is ready for use. (The “one layer at time” is the additive part.)



TIP

3D printers are much like the familiar desktop paper printers you already use at work or in your home to create copies of documents transmitted electronically or created on your computer, except that a 3D printer creates a solid 3D object layer-by-layer from a variety of materials rather than producing a flat paper document.

Since the time of Johannes Gutenberg, the ability to create multiple printed documents has brought literacy to the world. Today, when you click the Print button in a word processing application, you merge the functions of writers, stenographers, editors, layout artists, illustrators, and press reproduction workers into a single function that you can perform. Then, by clicking a few more buttons, you can post the document you created on the Internet and allow it to be shared, downloaded, and printed by others all over the world.

3D printing does exactly the same thing for objects. Designs and virtual 3D models of physical objects can be shared, downloaded, and then printed in physical form. It's hard to imagine what Johannes Gutenberg would have made of that.

Defining additive manufacturing

Why is additive manufacturing called *additive*? Additive manufacturing works by bringing the design of an object — its shape — into a computer model and then dividing that model into separate layers that are stacked to form the final object. The process re-imagines a 3D object as a series of stackable layers that forms the finished object. (See Figure 1-1.) Whether this object is a teacup or a house, the process starts with the base layer and builds up additional layers until the full object is complete.



TECHNICAL
STUFF

Before 3D printers were commonplace, another computer-controlled technique called subtractive manufacturing was developed. Almost exactly the opposite of 3D printing, this method cuts and mills a solid block of material — often metal — into the desired shape by the use of a computer program and series of instructions called GCODE. This same expanded instruction set is now also used for additive manufacturing.

An easy way to imagine the difference between additive and subtractive manufacturing is to think of building up a model by pressing and molding strips or coils of clay on top of each other. Alternatively, the same model could be carved from a block of stone (subtractive).

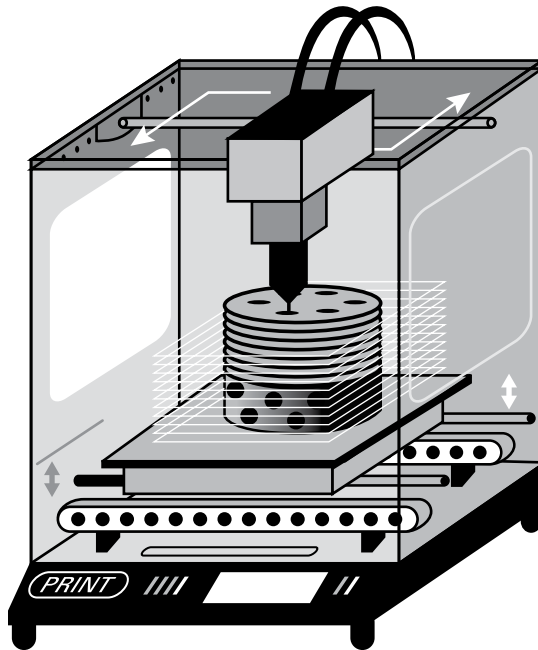


FIGURE 1-1:
A line drawing
showing how
3D printing
works.

When we were young, many of us built structures like houses using toy bricks. We placed a row of bricks to form the outer walls and then added more rows until we reached the height we wanted. A 3D printer does pretty much the same thing — laying down an extrusion of material (most often molten plastic) to achieve the same starting perimeter and then adding layers upon layers on top of the cooled plastic underneath.

3D printers build up layers of material in a few ways: by fusing liquid polymers with a laser, binding small granular particles with a laser or a liquid binding material, or extruding melted materials in the same way that toothpaste is squeezed from a tube onto a toothbrush. 3D printers, however, perform their additive manufacturing with many more materials than just toothpaste or cheese in a can. They can fabricate items by using photo-curable plastic polymers, melted plastic filaments, metal powders, concrete, and many other types of materials — including biological cells that can form amazingly complex structures to replace, repair, and even augment our own bodies.

Just as the rings of a tree show the additive layers of the tree's growth each year, additive manufacturing builds objects one horizontal layer at a time in a vertical stack. In this way, you can create a small plastic toy and even a dwelling; someday you'll be able to create complete airplanes with interlocking parts. Today's research on conductive materials is already proving successful with early 3D-printed electronic circuits and embedded printed components being printed directly in an object instead of being installed later.

Contrasting additive manufacturing with traditional manufacturing

How does this newfangled additive manufacturing compare to the traditional methods of subtractive production that have worked just fine since the first Industrial Revolution in the 1700s transformed manufacturing from hand production to automated production, using water and steam to drive machine tools? Why do we need to take up another disruptive technological shift after the second Industrial Revolution in the 1800s transformed the world through the increased use of steam-powered vehicles and the factories that made mass manufacturing possible?

In answering such questions, it helps to realize what the third Industrial Revolution that is coming our way actually entails: It means mass manufacturing and the global transfer of bulk goods will be set aside in favor of locally produced, highly personalized, individual production, which fits nicely with society's transition to a truly global phase of incremental local innovation.

The first Industrial Revolution's disruption of society was so fundamental that governments put in place trade restrictions in a desperate attempt to protect domestic wool textiles from power-woven cotton textiles being imported from other countries. The spinning jenny and automated flyer-and-bobbin looms allowed a small number of people to weave hundreds of yards of fabric every week; whereas hand weavers took months to card plant fibers or shorn hair, spin the material into thread, and weave many spools of thread into a few yards' worth of fabric. Suddenly, new industrial technologies such as the automated loom were putting weavers out of work, sparking the formation of the Luddite movement that tried to resist this transformation by smashing the textile machines they saw as destroying their livelihood. Fortunately, the capability of the new technologies to bulk produce clothing eventually won that argument, and the world was transformed.

A few years later, the second Industrial Revolution's disruption of society was even more pronounced, because automation provided alternatives not limited by the power of a man or horse, and steam power freed even massive industrial applications from their existence alongside rivers and water wheels, allowing them to become mobile. The difficulties traditional workers faced due to these new technologies are embodied in the tale of folk hero John Henry. As chronicled in the powerful folk song "The Ballad of John Henry," Henry proved his worth by outdigging a steam-driven hammer by a few inches' depth before dying from the effort. This song and many like it were heralded as proof of mankind's value in the face of automation. Yet the simple fact that the steam hammer could go on day after day without need for food or rest, long after John Henry was dead and gone, explains why that disruption has been adopted as the standard in the years since.

Here at the edge of the transformation that may one day be known as the third Industrial Revolution, the disruptive potential of additive manufacturing is obvious. Traditional mass manufacturing involves the following steps, which are comparatively inefficient:

1. Making products by milling, machining, or molding raw materials
2. Shipping these products all over the world
3. Refining the materials into components
4. Assembling the components into the final products in tremendous numbers to keep per-unit costs low
5. Shipping those products from faraway locations with lower production costs (and more lenient workers' rights laws)
6. Storing vast numbers of products in huge warehouses
7. Shipping the products to big-box stores and other distributors so they can reach actual consumers

Because of the costs involved, traditional manufacturing favors products that appeal to as many people as possible, preferring one-size-fits-most over customization and personalization. This system limits flexibility, because it's impossible to predict the actual consumption of products when next year's model is available in stores. The manufacturing process is also incredibly time-consuming and wasteful of key resources such as oil, and the pollution resulting from the transportation of mass-manufactured goods is costly to the planet.

Machining/subtractive fabrication

Because additive manufacturing can produce completed products — even items with interlocking moving parts, such as bearings within wheels or linked chains — 3D-printed items require much less finishing and processing than traditionally manufactured items do. The traditional approach uses subtractive fabrication procedures such as milling, machining, drilling, folding, and polishing to prepare even the initial components of a product. The traditional approach must account for every step of the manufacturing process — even a step as minor as drilling a hole, folding a piece of sheet metal, or polishing a milled edge — because such steps require human intervention and the management of the assembly-line process, which, therefore, adds cost to the product.



TIP

Yes, fewer machining techs will be needed after the third Industrial Revolution occurs, but products will be produced very quickly, using far fewer materials. It's much cheaper to put down materials only where they're needed rather than to start with blocks of raw materials and mill away unnecessary material until you achieve the final form. Ideally, the additive process will allow workers to reimagine 3D-printed products from the ground up, perhaps even products that use complex open interior spaces that reduce materials and weight while retaining strength. Also, additive-manufactured products are formed with all necessary holes, cavities, flat planes, and outer shells already in place, removing the need for many of the steps involved in traditional fabrication.

Molding/injection molding

Traditional durable goods such as the components for automobiles, aircraft, and skyscrapers are fabricated by pouring molten metal into casting molds or through extrusion at a foundry. This same technology was adapted to create plastic goods: Melted plastic is forced into injection molds to produce the desired product. Casting materials such as glass made it possible for every house to have windows and for magnificent towers of glass and steel to surmount every major city in the world.

Traditional mold-making, however, involves the creation of complex master molds, which are used to fashion products as precisely alike as possible. To create a second type of product, a new mold is needed, and this mold in turn can be used to create only that individual design over and over. This process can be

time-consuming. 3D printers, however, allow new molds to be created rapidly so that a manufacturer can quickly adapt to meet new design requirements, to keep up with changing fashions, or to achieve any other necessary change. Alternatively, a manufacturer could simply use the 3D printer to create its products directly and modify the design to include unique features on the fly. General Electric currently uses this direct digital-manufacturing process to create 24,000 jet-engine fuel assemblies each year — an approach that can be easily changed mid-process if a design flaw is discovered simply by modifying the design in a computer and printing replacement parts. In a traditional mass-fabrication process, this type of correction would require complete retooling and lengthy delays.

Understanding the advantages of additive manufacturing

Because computer models and designs can be transported electronically or shared for download from the Internet, additive manufacturing allows manufacturers to let customers design their own personalized versions of products. In today's interconnected world, the ability to quickly modify products to appeal to a variety of cultures and climates is significant.

In general, the advantages of additive manufacturing can be grouped into the following categories:

- » Personalization
- » Complexity
- » Part consolidation
- » Sustainability
- » Recycling and planned obsolescence
- » Economies of scale

The next few sections talk about these categories in greater detail.

Personalization

Personalization at the time of fabrication allows additive-manufactured goods to fit each consumer's preferences more closely in terms of form, size, shape, design, and even color, as I discuss in later chapters.

The iPhone case, for example. (See Figure 1-2.) In no time, people within the 3D-printing community created many variations of this case and posted them to services such as the Thingiverse 3D object repository (www.thingiverse.com).

These improvements were rapidly shared among members of the community, who used them to create highly customized versions of the case.

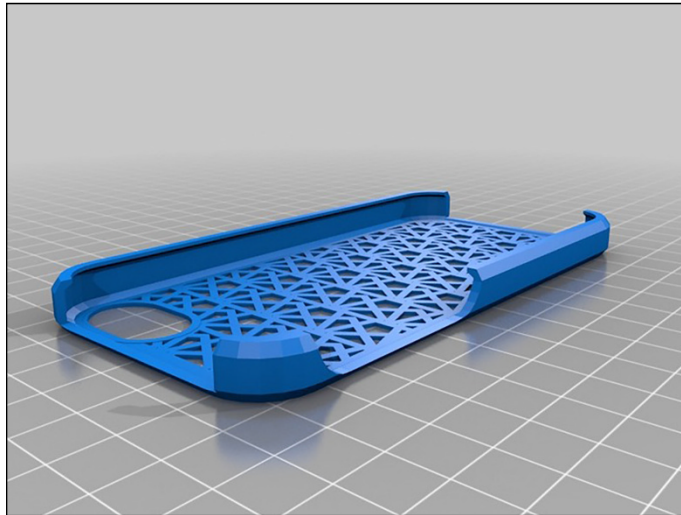


FIGURE 1-2:
A free downloadable, 3D-printable phone case for the iPhone.



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Sharing communities operate under what is known as Creative Commons licensing, which involves several copyright licenses developed by the nonprofit Creative Commons organization (<https://creativecommons.org/licenses/>), reserving some specific rights and waiving others to allow other creators to share and expand on the designs without the restrictions imposed by traditional copyright. In Part 4 of this book, I explain more about licensing and attribution.



TIP

If you use a 3D object file designed by someone else, take care to check what license the model is being distributed under; there may be restrictions on how you can use the file — printing may be allowed, for example, but modifications may not. Sharing the file may be okay, but selling a 3D-printed object made from the file may be restricted.

Complexity

Because all layers of an object are created sequentially, 3D printing makes it possible to create complex internal structures that are impossible to achieve with traditional molded or cast parts. Structures that aren't load-bearing can have thin or even absent walls, with additional support material added during printing. If strength or rigidity are desired qualities, but weight is a consideration (as in the frame elements of race cars), additive manufacturing can create partially filled internal voids with honeycomb structures, resulting in rigid, lightweight products. Structures modeled from nature, mimicking items such as the bones of a

bird, can be created with additive-manufacturing techniques to create product capabilities that are impossible to produce in traditional manufacturing. These designs are sometimes referred to as *organic*.

When you consider that this technology will soon be capable of printing entire houses, as well as the materials therein, you can see how easily it can affect more prosaic industries, such as moving companies. In the future, moving from one house to another may be a simple matter of transferring nothing more than a few boxes of personalized items (such as kids' drawings and paintings, Grandma's old tea set, and baby's first shoes) from one house to another. There may come a time when you won't need a moving company at all; you'll just contact a company that will fabricate the same house and furnishings (or a familiar one with a few new features) at the new location. That same company could reclaim materials used in the old building and furnishings as a form of full recycling.

Sustainability

By allowing strength and flexibility to vary within an object, 3D-printed components can reduce the weight of products and save fuel. One aircraft manufacturer, for example, expects the redesign of its seat-belt buckles to save tens of thousands of gallons of aviation fuel across the lifetime of an aircraft. Also, by putting materials only where they need to be, additive manufacturing can reduce the amount of materials lost in postproduction machining, which conserves both money and resources.



Additive manufacturing allows the use of a variety of materials in many components, even the melted plastic used in printers such as the RepRap devices described in Chapter 11. Acrylonitrile butadiene styrene (ABS), with properties that are well known from use in manufacturing toys such as LEGO bricks, is commonly used for home 3D printing, but it's a petrochemical-based plastic. Environmentally conscious users could choose instead to use plant-based alternatives such as polylactic acid (PLA) to achieve similar results. Alternatives such as PLA are commonly created from corn, beets, or potato starch. Current research on producing industrial quantities of this material from algae may one day help reduce our dependence on petrochemical-based plastics and lower the need to use food-based crops.

Other materials — even raw materials — can be used. Some 3D printers are designed to print objects by using concrete or even sand as raw materials. Using nothing more than the power of the sun concentrated through a lens, Markus Kayser, the inventor of the Solar Sinter, fashions sand into objects and even structures. Kayser uses a computer-controlled system to direct concentrated sunlight precisely where needed to melt granules of sand into a crude form of glass, which he uses, layer by layer, to build up bowls and other objects. (See Figure 1-3.)

FIGURE 1-3:
A glass bowl
formed by
passing sunlight
through the
Solar Sinter to
fuse sand.



Image courtesy of Markus Kayser

Recycling and planned obsolescence

The third Industrial Revolution offers a way to eliminate the traditional concept of planned obsolescence that's behind the current economic cycle. In fact, this revolution goes a long way toward making the entire concept of obsolescence obsolete. Comedian Jay Leno, who collects classic cars, uses 3D printers to restore his outdated steam automobiles to service, even though parts have been unavailable for the better part of a century. With such technology, manufacturers don't even need to inventory old parts; they can simply download the design of the appropriate components and print replacements when needed.

Instead of endlessly pushing next year's or next season's product lines (such as automobiles, houses, furniture, or clothing), future industries could well focus on retaining investment in fundamental components, adding updates and reclaiming materials for future modifications. In this future, if a minor component of a capital good such as a washing machine fails, a new machine won't need to be fabricated and shipped; the replacement will be created locally, and the original returned to functional condition for a fraction of the cost and with minimal environmental impact.

Economies of scale

Additive manufacturing allows individual items to be created for the same per-item cost as multiple items of the same or similar designs. By contrast, traditional mass manufacturing requires the fabrication of huge numbers of identical objects to drop the per-item cost passed along to the consumer.

Additive manufacturing, as it matures, may engender a fundamental transformation in the production of material goods. Supporters present the possibility of ad-hoc personalized manufacturing close to consumers. Critics, however, argue about the damage of this transition on current economies. Traditional manufacturing depends on mass manufacturing in low-cost areas, bulk transportation of goods around the world, and large storage and distribution networks to bring products to consumers.

By placing production in close proximity to consumers, shipping and storing mass-produced goods will no longer be necessary. Cargo container ships, along with the costs associated with mass-manufacturing economies, may become things of the past.

It may be possible to repurpose these immense cargo ships as floating additive-manufacturing centers parked offshore near their consumer base as the world migrates away from traditional mass-manufacturing fabrication centers. One potential advantage of this shift would be that manufacturers of winter- or summer-specific goods could simply float north or south for year-round production to meet consumer demand without the issues and costs associated with mass manufacturing's transportation and storage cycles. Also, following a natural disaster, such a ship could simply pull up offshore and start recycling bulk debris to repair and replace what was lost to the elements.

During the 2020 global pandemic many industries ground to a halt. Businesses found it impossible to continue with traditional supply methods due to transport delays and an extended backlog of work, the unavailability of raw materials, and the shutdown of traditional manufacturing processes. Having on-site manufacturing in the form of 3D printers has helped many companies continue with both the current production and ongoing development of future products without the need for outside assistance. You do, however, need to have the raw materials in stock, but a small selection of plastic filament wire can allow the production of thousands of different components when needed with minimal waste or delay.

WORKING WITH RepRap

The first 3D printer was patented in the late 1980s, and the rate of change was fairly minimal for 30 years. Labs and research departments did start using early 3D printers in rapid prototyping systems that quickly produced mockups of industrial and consumer products, but things really took off after British researcher Adrian Bowyer created the first self-replicating rapid prototyping (RepRap) system by using salvaged stepper motors and common materials from the local hardware store. The *self-replicating* part of the name means that one RepRap system can print many of the components of a second 3D-printer system.

In Part 5 of this book, I look at many 3D printers that have descended from the RepRap project. Almost all desktop 3D printers available today are based on technology created and released as part of the open-source hardware RepRap project and its many “survival of the fittest” descendants.

Exploring the Applications of 3D Printing

Without doubt, additive-manufacturing technologies will transform many industries and may even return currently outsourced manufacturing tasks back to local manufacturing. This transformation in turn may well affect industries involved in the transportation and storage of mass quantities of products, as well as the materials (and quantities thereof) used in the production of goods. When you look at the possible effects of the third Industrial Revolution — 3D printing, crowd-funding, robotics, ad hoc physical media (models) content, and a host of other technologies — you see a means to not only alter the course of production, but also fundamentally shatter traditional manufacturing practices.

In the chapters ahead, I show you the current state of the art of 3D printing — what the technology can and can’t do now — and what it may do one day to transform the world into an agile, personalized, customized, and sustainable environment. I show you the types of materials that can be used in additive manufacturing, and I provide some ideas about the materials that may soon become available. I show you how to create or obtain 3D models that are already available and how to use them for your own purposes and projects. Many 3D objects can be designed with free or inexpensive software and photos of real objects, such as historical locations, antiquities in a museum, and children’s clay creations from art class.



REMEMBER

Whether you use a 3D-printing service or a home desktop 3D printer, you should take several considerations into account before creating your own 3D-printed objects; these considerations (design for the 3D-printing process) are really important for successful results and are discussed in Chapters 5 and 16.

- » Getting to know basic additive manufacturing
- » Understanding specialized additive manufacturing
- » Seeing what current technologies lack

Chapter 2

Exploring the Types of 3D Printing

Whenever you discuss additive manufacturing, direct digital fabrication, rapid prototyping, or 3D printing, you're talking about the same process: translating a 3D design stored in a computer into a stack of thin layers and then manufacturing a real, physical object by creating those layers, one at a time, in a 3D printer. This chapter discusses current applications — and limitations — of this technology.

Exploring Basic Forms of Additive Manufacturing

To translate a 3D virtual model's design into the stack of layers that make up an object, all 3D printers require the unique coordinates of every element of the object to be fabricated.



TIP

Some 3D printers work across a level surface called the *build plate*, whereas others create objects atop successive layers of granulated material. Some of the RepRap printers discussed in this book are of two types: *Cartesian*, which uses motors to move in the X, Y, and Z directions (see Figure 2-1) and *Delta*, which relies on

mechanical linkages to three motors to move an extruder within the entire build volume. (Even Delta-type 3D printers require X, Y, and Z coordinates into which they extrude the build material for the final object.)

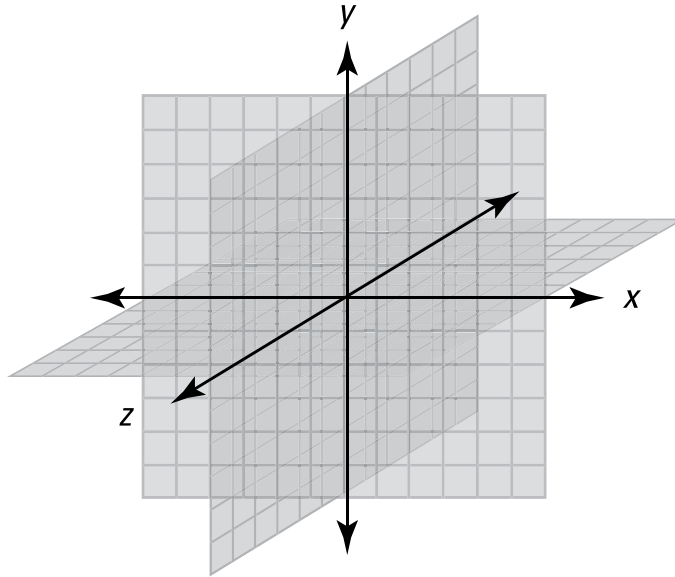


FIGURE 2-1:
Coordinates
using X-, Y-, and
Z-axis notation.

These printers are designed to accommodate the properties of the materials from which they create objects. The most common material types are

- » Photopolymers
- » Granular powders
- » Laminates
- » Composites and mixed materials
- » Filament-based production (plastic wire for FDM-based 3D printers)

The next sections look at each material type in greater detail.

Photopolymers

Photopolymers are materials that can transform from a liquid to a solid almost instantaneously when the right kind of light shines on them. These materials are great for additive manufacturing.

The first type of additive manufacturing was termed *stereolithography* by its inventor, Charles W. Hull, who founded (and continues to lead) 3D Systems. From the word *stereolithography* comes the standard 3D-printed object file type, STL, invented by Hull in the late 1980s. Today's 3D printers and software use the STL file type for most common printing operations; a few more modern file types are emerging as new variations of full-color and blended-material 3D printing become possible. Stereolithographic (SLA) fabrication is often used for high-resolution object manufacturing, providing highly detailed surfaces, as in the case of jewelry master designs for molding and casting.

Stereolithography uses focused ultraviolet light to transform liquid photopolymer plastic into solid form. (See Figure 2-2.) The process takes place on a movable platform above a reservoir of the photopolymer plastic. The platform submerges into the reservoir just enough to create a thin layer of liquid. A beam of ultraviolet laser light is drawn over the liquid to create the first hardened layer of the object. By lowering the platform to allow more liquid to cover the first layer, the machine operator can construct the second layer atop the first. Each layer must connect to the one below or to a support structure that can be removed later to keep the object from floating out of position as the new layers are added and more fluid polymer is poured atop them.

Stereolithographic formation of objects provides excellent detail (see Figure 2-3), but the materials are currently limited to UV or daylight-activated liquid polymers that can be cured to solid states under a focused beam of light or with a laser. Recent developments include Direct Light Processing (DLP) light projection of an entire layer at the same time across the bottom of the build volume, curing each layer as the object is raised out of the polymer liquid from atop a full-screen light source.

High-resolution variations of stereolithography use lasers focused so tightly that individual elements of the final object are microscopic. Such nano-scale lithographic designs have created entire buildings so small that they could be lost entirely in a single drop of water. The rendering of the Brandenburg Gate shown in Figure 2-4 is only a fraction of a millimeter in height.

Objet's PolyJet system also uses photopolymerization but uses inkjet materials to build up the layers. This system doesn't rely on a bath of liquid; instead, it keeps the materials in separate cartridges within the printer during operation (and can even mix materials as it sprays them), hardening the applied spray with ultraviolet light after each pass. (See Figure 2-5.) With this approach, you can create seemingly impossible printouts, such as a ship in a transparent bottle or a fetus gestating within a transparent belly.

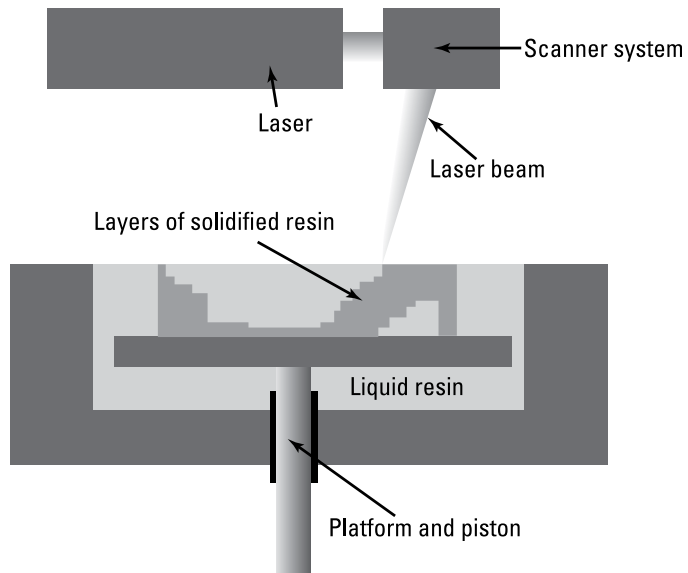


FIGURE 2-2:
How stereolithography works.



FIGURE 2-3:
Object created via stereolithography on a FormOne printer.

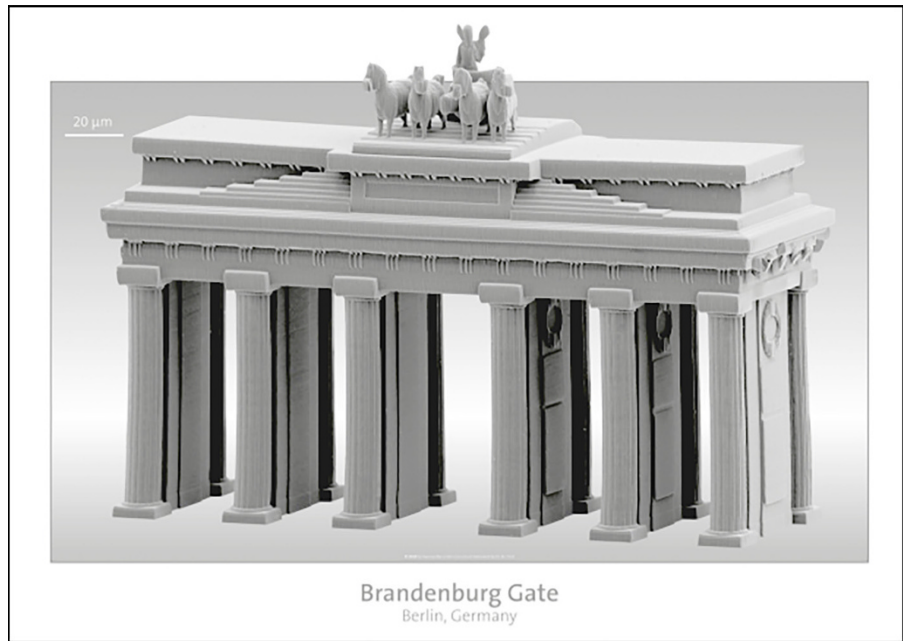


FIGURE 2-4: Object created via multiphoton lithography on a NanoScribe 3D printer.

Image courtesy of NanoScribe

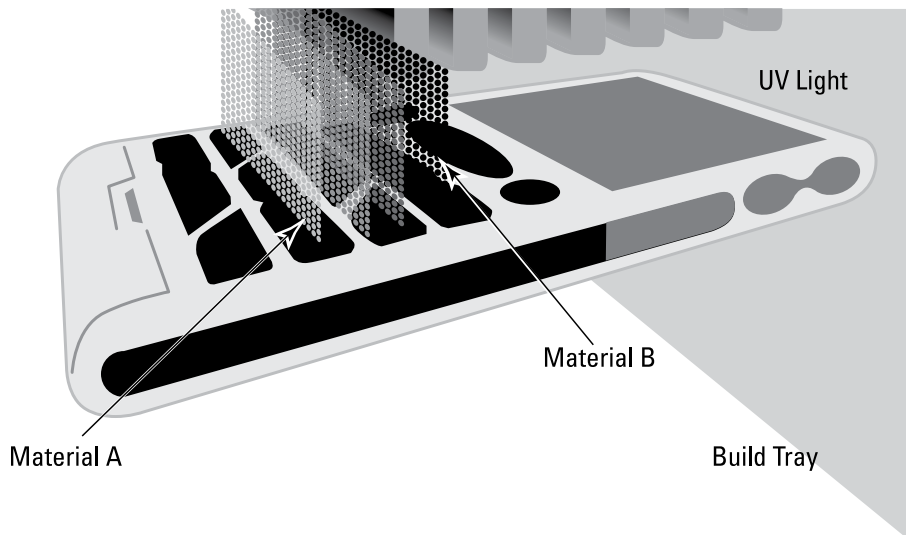


FIGURE 2-5: Objet's photopolymer PolyJet printer can mix multiple types of materials.

The PolyJet's capability to mix materials also allows for different functionalities within the same printed material. (Refer to Figure 2-5.) This means that complex objects, such as a prosthetic arm or foot — a flexible joint sandwiched between hard-plastic components — can be printed in a single process. Using this

approach, you can create combinations of materials — part rubber and part solid plastic, for example — in a single printed item. Good examples of this type of prototyping include a cellphone with a hard plastic shell and rubber grip panels and a toy car with a rigid plastic wheel and rubber tires.



You can see the detail and personalization that these multimaterial printers can produce in objects used in major movies. Objet's printer, for example, was used to create the armor that fit Robert Downey, Jr., like a glove in the *Iron Man* movies. The printer also allowed the effects team for the blockbuster *Prometheus* to produce and custom-fit bubblelike space helmets for the actors.

Granular powders

Another technique, popular for plastics, metals, and even ceramics, relies on granular powders. This technology has been used to create large objects, such as James Bond's car in *Skyfall*, as well as flexible artwork such as 3D-printed dresses. The granules can be solidified in a variety of ways:

- » Binding the granules with bonding materials such as glues
- » *Sintering* (combining powders by heating them below their melting point, as shown in Figure 2-6)
- » Melting (combining powders by heating them above their melting point to create a full melt pool of material, using a laser or electron beam to provide the energy necessary to fuse the powder only where the final object needs to be)

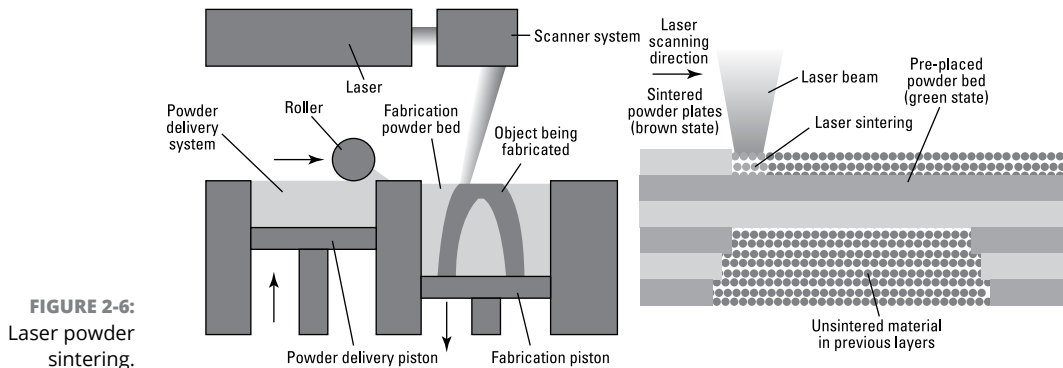


FIGURE 2-6: Laser powder sintering.

Binding powder

Powder-binding printers use inkjet sprays to apply a rapidly solidified binder to the powder bed, creating the new solid object from this sprayed glue and the base

powder material. When the entire model is complete, unused powder is removed and recovered for reuse, as shown in Figure 2-7.

FIGURE 2-7:
Extracting a piece
of 3D-printed
clothing from a
granular binding
powder bed.

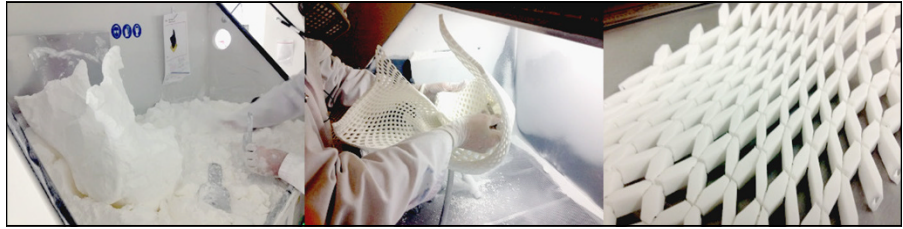


Image courtesy of Francis Bitonti Studio

Plastic-powder objects remain granular, so they can easily be crushed unless they're dipped in a resin that fills the spaces between the granules. For metal and glass casting, the resulting "solid" shapes are stabilized by heating them to fuse the binder and powder. Simple metal powder can be infused with additional liquid metals (such as bronze) to create a stronger alloy or more pleasing appearance. This technique is popular in jewelry making, because precious metals such as gold and silver are too expensive to keep in granular form to fill the powder bed. Also, the use of powder granules from a more common source decreases the cost of materials.

Because the powder bed supports the solidified bound material, this type of production allows you to create large, complex designs without concern that thinner elements will break apart during fabrication. One vendor, VoxelJet, uses the powder bed's support to allow continuous creation of objects. The system uses a binding jet that operates across a tilted granular bed and a conveyor belt that moves the entire volume of powder slowly through the printer. In this way, the printer builds models by adding powder along the incline layer by layer (see Figure 2-8) and selectively binding the powder according to the 3D design. You can even use this technique to fabricate solid objects that are longer than the entire printer's depth by continually printing the front end of the model as the rear extends beyond the conveyor behind the printer.

Blown powder

Another technique used in metal fabrication involves blowing metal powder into a laser or electron beam; adding the blown powder to the melt pool formed by the heat source fuses the material together. This technique is particularly useful when the materials require exceptionally high levels of heat to melt; examples include tantalum and titanium used in aircraft manufacturing. As in the other forms of additive manufacturing, you can apply blown powder very exactly to create complex final parts with no more effort than creating a simple design that uses the same amount of material. (See Figure 2-9.)

FIGURE 2-8:
A VoxelJet
powder
bed binding
3D printer
prints along
an inclined
plane.

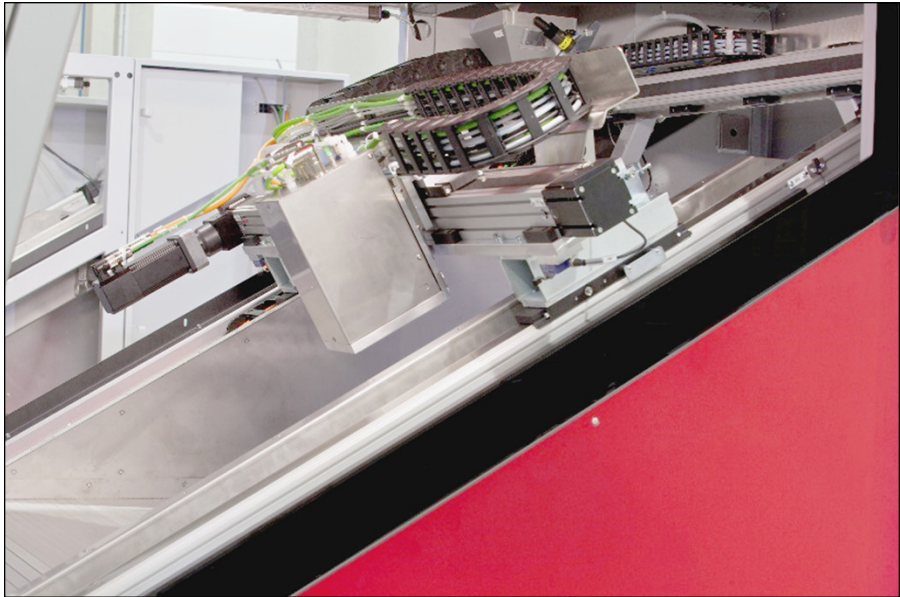


Image courtesy of VoxelJet

FIGURE 2-9:
A titanium cooler
block created
with EOS's
Direct Metal
Laser-Sintering
(DMLS)
3D printer.



Image courtesy of WithinLab

Laminates

Another type of additive manufacturing, *lamination*, uses a rather different approach. Instead of laying down layers of powders or melting pools of material, lamination cuts individual layers of material and then stacks them, one atop another, with a form of glue. You can create laminated objects from metal foils, plastic sheets, and even common paper.

The final product, however, is only as strong as the material it's made of: paper, foil, or plastic, together with the glue. Also, laminated object-manufacturing systems lack resolution on the Z axis (as the object gets taller) because each layer height is fixed at the thickness of the sheet of material plus the layer of glue. Still, these systems can be very attractive to people who need models for rapid prototyping of products and prefer inexpensive, rapid assembly to higher-resolution alternatives.

Filament-based production

Perhaps the best-known form of additive manufacturing is fused filament fabrication (FFF). Using STL files (refer to “Photopolymers” earlier in this chapter), an FFF 3D printer squeezes melted thermoplastics through a small nozzle to create an object. The process is much like squeezing toothpaste from a tube to cover a toothbrush. The printer builds layers of melted plastic to create an object that can cool to room temperature in a matter of minutes. (See Figure 2-10.)

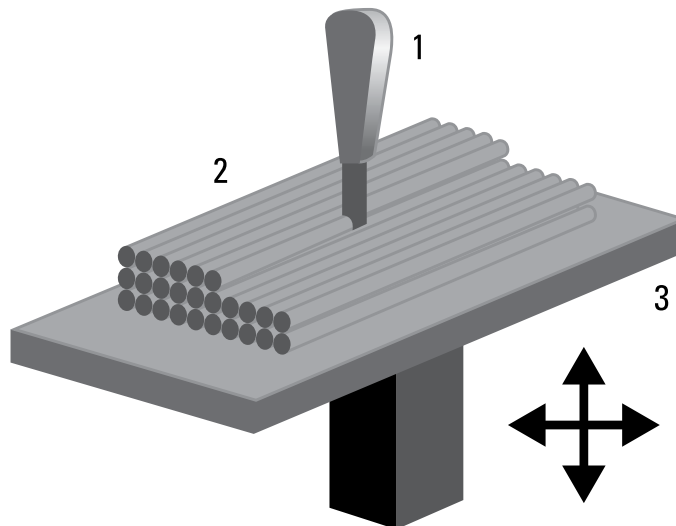


FIGURE 2-10:
Fused filament
fabrication.



TIP

You may also hear FFF referred to as *fused deposition modeling* (FDM), a term that's trademarked by Stratasys.



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The thermoplastic used in this type of 3D printer is typically sold in spools of thin filament in two diameters: 1.75mm and the now much less common 2.85mm standard. This filament can be made of acrylonitrile butadiene styrene (ABS) polymer, polylactic acid (PLA) bioplastic, water-soluble polyvinyl alcohol (PVA), nylon, or composite materials. One experimental wood/plastic composite filament (see Figure 2-11) can be sanded and painted like wood; it can even be given a grainlike pattern by varying the temperature at which it's squeezed out.

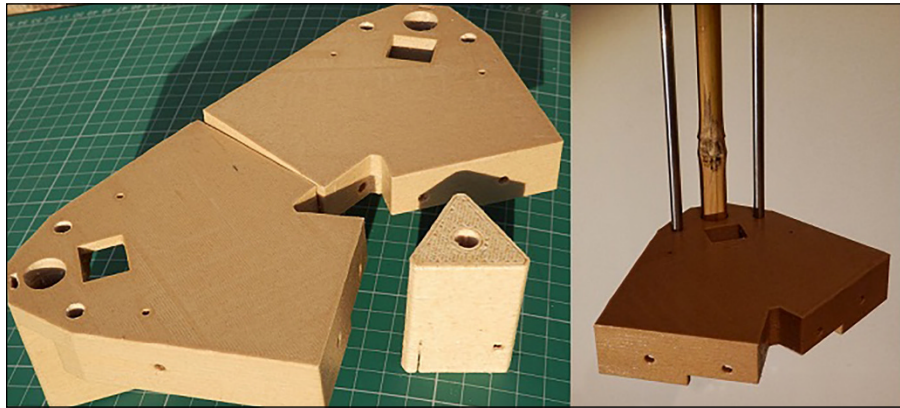


FIGURE 2-11:
An example
wood/plastic
composite.

Understanding the Limitations of Current Technologies

The potential for additive manufacturing is little short of miraculous, but several factors will affect the speed of the transformation from traditional, subtractive manufacturing to additive manufacturing. I discuss those factors in the following sections.

Considering fabrication rates

Cultural expectations of instant fabrication were set by Hollywood: The simple statement “Tea, Earl Grey, hot” by an actor on *Star Trek: The Next Generation* was quickly rewarded by a cup of hot tea. These expectations are too high. Today's technologies take minutes or even hours to create a plastic cup — never mind water and tea to fill it. The object may be hot, depending on the technique used to fabricate it, so perhaps it's only a matter of time before you can order a cup of hot tea *Enterprise*-style.

Newcomers to 3D printing are often taken aback by how long it takes to print even small plastic items — several hours in most cases. Some of the items shown in magazines and on TV specials about 3D printing are amazing, but they may be composed of hundreds of pieces, each of which takes time to design and then print — assuming that everything works perfectly the first time. The benefit of additive manufacturing is that any complex features that would take a long time to produce through traditional means (holes through the object, stamped serial numbers, and so on) can be printed in the same time it takes to print the same model without those details.

Exploring size constraints

Most 3D printers have a specific volume within which they can create their output. For some printers, a *Star Trek* teacup might be too large; others can produce a full-scale chair in a single print. The concept of constrained build volume, however, may be eliminated when open-form systems such as a fully articulated 6D robot arm or gantry with multiple tool-changing extruders are perfected.

Identifying object design constraints

In addition to having to fit within the printer, an item has to be printable in the first place. Experience in design and materials science can help, but also an understanding of how the object is being built layer-by-layer can guide a designer on how to work with the 3D-printing process for greater success. (I go over designing specifically for 3D printing in Chapter 16.)

All forms of manufacturing have unique constraints. Anyone who's familiar with injection molding, for example, knows that the process requires channels for air to escape the mold when filler material is forced in. Additive manufacturing is no different. Several considerations unique to 3D printing are already commonplace.

Some types of 3D printing require an effective support structure that can be removed later, as well as a specific amount of overhang so that each layer can be aligned atop the one prior to it without gaps or drooping edges.

Also, the software used to design printable objects takes some experience to master, although the software needn't be expensive. Several alternatives for home use are free or much less expensive than the thousands of dollars per copy that many professional 3D modeling software packages command. You can expect that whole category of software to continue improving rapidly as more people are exposed to this technology in early education. New software is starting to handle full-color object designs, complex internal voids and structures, interlocking components in the same build volume, and qualities based on a unique mix of materials at each

point in the build. I discuss software requirements and options unique to 3D printing in Chapter 11 and beyond.

Understanding material restrictions

The variety of new materials that can be used in 3D printers is expanding too quickly for me to enumerate here. The Objet PolyJet system alone uses more than 100 types of materials. Other manufacturers are offering ever-expanding suites of options for materials and fabrication techniques.

Whereas the bioprinters of 2015 were hard-pressed to produce anything approaching a functional artificial cartilage, today, 3D-printed organs based on a 3D-printed scaffold for lab grown cells are being tested. Someday, you may be able to print a steak for your home barbecue or a 3D replacement for your aging knee. One day, 3D-printed heart replacements or new muscular enhancements printed directly into our bodies may be as common as 3D-printed silverware. (See Figure 2-12.)



FIGURE 2-12:
3D-printed silver
forks.

Image courtesy of Francis Bitonti Studio



REMEMBER

Fabrication techniques are being refined, but they aren't perfect. Compared with injection-molded items, the fused thermoplastic objects created by today's printers have minor weaknesses along each layer's boundary. Both bonded and sintered granular materials have a more complex — and potentially fragile — inner structure than the solid forged or molded alternatives, but they also weigh far less and may prove to have surprising capabilities that their predecessors' makers could never have dreamed of. The use of new sustainable materials such as PLA (a biodegradable plastic derived from plant starch) can be recycled and may aid in the adoption of 3D-printed products. All revolutionary change brings both new requirements and new capabilities.

- » Exploring current uses of 3D printing
- » Developing new products with 3D printing
- » Using 3D printing for molding and casting
- » Customizing printed objects
- » Tweaking existing designs

Chapter **3**

Exploring Applications of 3D Printing

The promise of additive manufacturing is that it makes possible the local, on-demand creation of any product in a fully personalized manner. Enthusiasts of additive manufacturing see that day as being just around the corner. Supporters of 3D printing see in this promise the possibility that 3D printing will repatriate manufacturing functions and manufacturing jobs to local communities; reduce waste materials; eliminate the need for spare parts; and use biodegradable, sustainable alternative materials in place of the durable petroleum-based plastics that currently pour into landfills.

Despite the advantages of this new paradigm, critics of additive manufacturing exist. Some are already implementing campaigns to discredit 3D-printing objects by asking questions such as “When a car crashes because of a 3D-printed part, who is legally liable?” Beyond the fundamental assumption that a car would fail only because of a 3D-printed part, many parts and components are already being designed, tested, prototyped, and even manufactured via additive manufacturing, and in some fields, this has been the case for decades.

No matter how you look at it, additive manufacturing will affect the way that people manufacture goods. Already, the process is being used to augment mass-manufacturing factories and processes. One day, perhaps, this technology will be the only means of manufacturing goods, and every product will be subject to local fabrication and full personalization. Traditional manufacturing practices have a deep hold on the economy and will continue to exist essentially unchanged for some time. But even in traditional settings, additive manufacturing has caught hold and is helping in the creation of products that people use daily.

In this chapter, I discuss current applications of additive manufacturing technologies.

Looking at Current Uses of 3D Printing

As discussed in Chapter 2, several types of additive manufacturing are already being used to manufacture objects from plastic, resin, metal, and many other materials. Current applications include prototyping and direct digital fabrication, as I explore in the following sections.

Rapid prototyping

The earliest use of 3D printing was in producing digitally designed objects as prototypes of new designs (see Figure 3-1). The advantages of rapid prototyping with additive manufacturing include the following:

- » Evaluating a design while it's still in the computer
- » Creating a solid prototype that can be handled and operated
- » Comparing the printed prototype with components of existing systems to ensure correct fit and function

Creating a solid object for consumers to evaluate speeds the rate at which new designs can be compared. 3D-printed versions of alternative designs can be reproduced and compared much more quickly than individual examples of each design can be turned out, saving weeks in the production schedule.

Often, a prototype doesn't need the material strength of the final object, so manufacturers can use a plastic or resin design to test an object before investing in the cost and materials required for final reproduction. Jewelers, for example, can test their designs in wax or biodegradable plastic at a cost of a few cents and create their final models in gold, silver, or other valuable materials after the client approves the fit and function.

3D-printed prototypes can also illustrate additional details for product evaluation by means of color and other indicators; information such as stress load or thermal measure within a structured object can be clearly represented for nontechnical review. This same capability can illustrate the visual impact of different artistic or coloring options and build marketing materials to allow early review by test audiences.

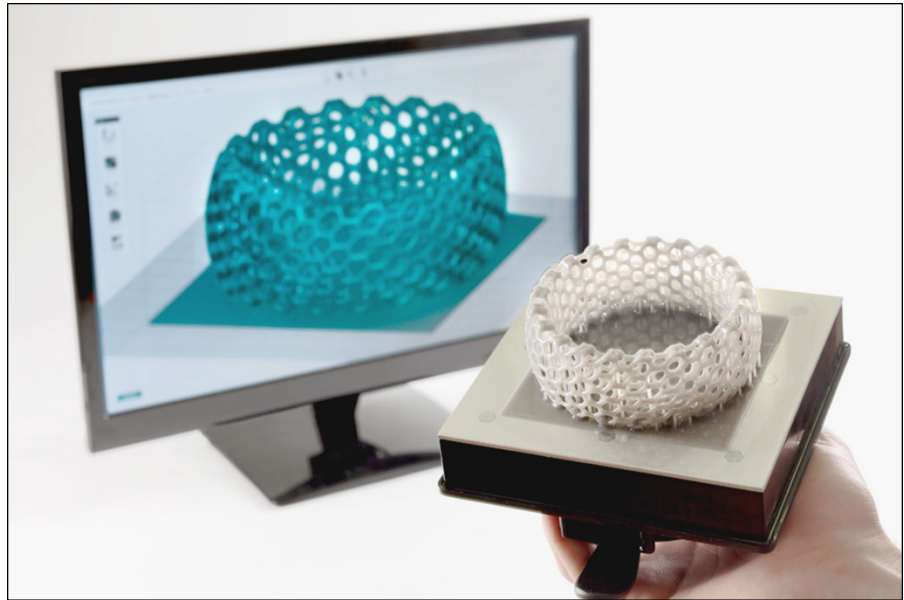


FIGURE 3-1:
Rapidly prototyping a new digital design for a bracelet.

Image courtesy of FormLabs

Direct digital fabrication

Creating prototypes via additive manufacturing speeds the stages of the design process, but creation doesn't stop there. In metal fabrication systems, additive manufacturing can create final products and designs rather than just plastic prototypes. Details such as serial numbers, branded marketing designs, and even interlocking and joined structures, such as a chain or zipper, can be included in the physical structure of the product, with no tooling steps needed beyond the 3D-printed output.

Producing a single unique design (called a *one-off*) or another limited-production run for a specialty product, such as those used in racing, medical, and space technologies (see Figure 3-2), can be costly in traditional manufacturing. Because the same mold or tooling is used only a few times, or possibly once, no opportunities exist for efficiencies of scale that bring down per-item costs in mass manufacturing.

FIGURE 3-2:
A lightweight
intake cooling
system for race
cars, created with
a complex
interior set of
voids to reduce
weight in the
whole car.

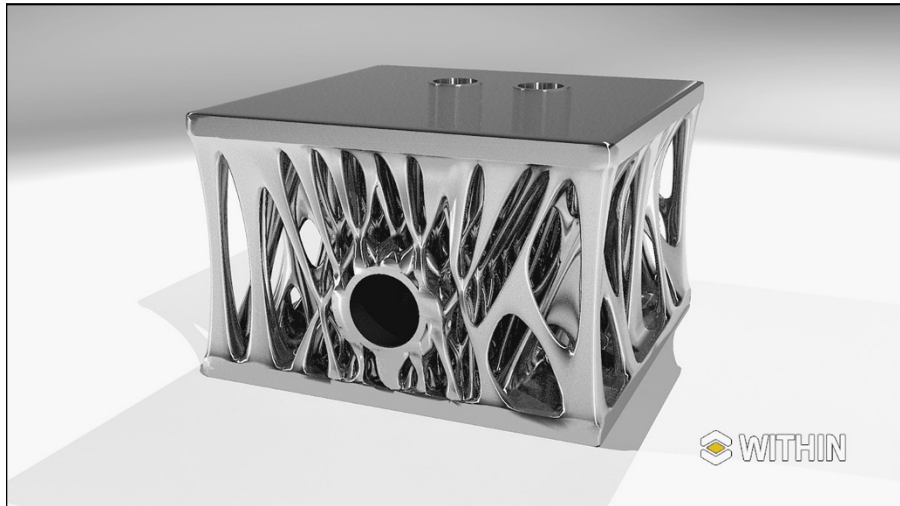


Image courtesy of WithinLab

Direct digital manufacturing also allows updates in the middle of a production cycle without the need to retool the production line. When the digital model is modified and uploaded to the 3D printer, all future items include the change automatically. General Electric has started using this capability in the design of its future aircraft jet engines. Rapid updates keep the line in operation and save time in the production of high-precision engine components because multiple components can be combined and printed at the time. This technique doesn't require the traditional methods of brazing and welding to combine individual assemblies.

Restoration and repair

Additive manufacturing can be used to re-create objects that have been removed from available inventory stocks to make room for new models or that have become largely obsolete.

Components such as a compressor cover for a steam-powered car or a replacement flipper for a pinball machine (see Figure 3-3) are long gone from the corner store, whether or not they were ever available to the public. (See Figure 3-4.) By scanning the broken parts of an existing design or creating a new replacement part from measurements and CAD design, additive manufacturing can bring new life to outdated designs. 3D-printed parts can be further strengthened by coating the part filler, paint, or by adding liquid resin, cement, or flexible glues into the interior of the print. Postprocessing or strengthening may allow the direct use of a printed part in the end application.

FIGURE 3-3:
A replacement
flipper for a
pinball machine,
shared as
THING #1789
on Thingiverse
(<http://www.thingiverse.com/thing:1789>).

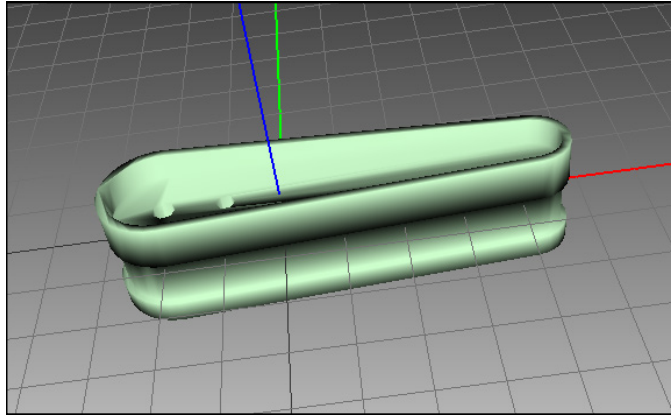


FIGURE 3-4:
A metal table
illustrating
function and fluid
form.



Image courtesy of the Francis Bitonti Studio (designer Michael Schmidt, architect Francis Bitonti)

By creating designs that can take the place of original equipment, manufacturers can improve on the originals, making the repaired item better than new. You can use new materials, add reinforcements, and make any modifications entirely within the computer before creating a part. And when you create the part in light-weight, inexpensive plastic, you can test its fit and make further adjustments before creating the final object in the desired material.

This new parts-management technique means that manufacturers no longer need to store copies of all possible parts in warehouses and other locations. Instead,

they can simply download the design of the appropriate component and print its replacement when needed. Instead of waiting days or weeks for a replacement part for your car to be shipped to a local dealership, you could call the mechanic to schedule a recall item replacement, and the mechanic would print the part to have it ready when you arrive. A complete warehouse full of individual parts could be replaced by a small shop stocking only raw materials and a bank of 3D printers. No items will be out of stock, and options could include different materials for special needs or personalized designs based on standard fittings or connectors.

Designing for the Future with 3D Printing

Building better, cheaper goods for existing product development cycles has many advantages, but the true power of additive manufacturing lies in the new opportunities, products, and services that 3D-printing technologies will make possible. The following sections describe some of these opportunities.

Household goods

Today, you might 3D-print a wall hook to use for hanging a photograph on your wall. The photograph itself could be 3D-printed in full color as a single object that includes a frame, as well as a cover pane of transparent plastic that gives the photo the same look and feel as a traditional framed picture. As more materials and complex assemblies are created through additive manufacturing, new products can be fabricated with the same color, shape, and function as the originals (see Figure 3-4).

As additive manufacturing technology improves in sophistication — to the point of printing complex, multiple-material objects such as integrated electronics and composite interlocking structures — the range of printable objects will expand. Eventually, you'll be able to 3D-print many items that you commonly use around the house — and the house itself!

Buildings

Soon, much larger 3D printers that extrude concrete may fabricate complete structures, like the one shown in Figure 3-5, intact. Human contractors wouldn't be required to assemble individual components and affix those assemblies to a foundation; the final structure would emerge from the printer.



FIGURE 3-5:
A model of a 3D
printer for
houses.

Image courtesy of Contour Crafting

Emergency shelters created for use after natural disasters such as hurricanes, earthquakes, and tidal waves could be replaced by solid shelters formed from natural materials present in the local environment, such as the open structural framework in Figure 3-6. This illustration is a small-scale creation formed by focusing concentrated sunlight on sand, found on beaches and in deserts around the world. The 3D printer merely moves the focal point across the sand to fuse individual granules into solid structures.

Additive manufacturing techniques also allow the creation of complex interior spaces to accommodate wiring, plumbing, and insulation. This process is quicker and more efficient than creating such spaces in traditional concrete slabs poured in wood frames. Figure 3-7 shows the creation of a corrugated concrete wall. This wall could retain its empty air pockets, or those gaps could be filled with materials such as foam or dirt to provide greater thermal protection. This process provides the same structural support capacity as traditional construction but uses far less material and doesn't generate scraps, cutoffs, and leftover material. Eventually, even plumbing and wiring will be fabricated directly into the structure itself.

Even now, the industry is on the verge of printing homes — or entire high-rise buildings — by using 3D printers that climb up the buildings that they're creating, lifting themselves to build one floor at a time (see Figure 3-8). This model is constructed much as the ancient Egyptians constructed the Pyramids at Giza, but such printed buildings could have complex curved walls instead of traditional stick-frame construction.



FIGURE 3-6:
A structure
created by using
sunlight to
fuse sand.

Image courtesy of Markus Kayser



FIGURE 3-7:
Corrugated wall
made of 3D
extruded
concrete.

Image courtesy of Contour Crafting

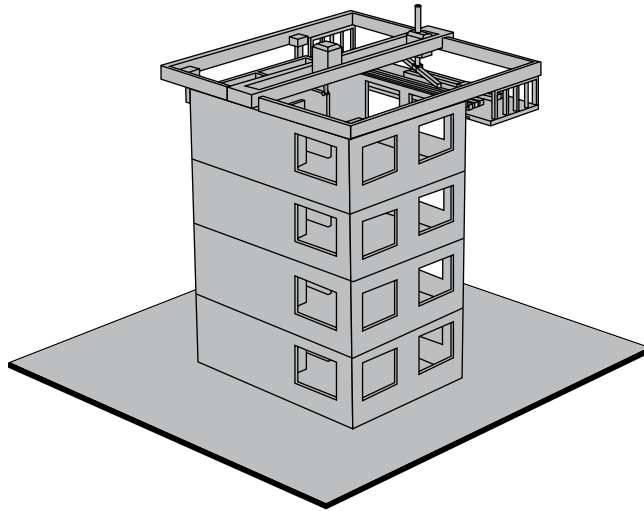


FIGURE 3-8:
3D printers that climb as they build can create multiple-floor buildings.

Image courtesy of Contour Crafting

Bridges

Europeans are building bigger designs such as walls and bridges. A pair of robotic arms can print a full-size bridge in its intended location (visit <http://mx3d.com/projects/bridge/> for more information) rather than pieces and parts to be assembled. The bridge can be completed in less time than traditional manufacturing would take. Printing a single unit also produces far fewer spare parts that would have to be sold or discarded.

Examining Molding and Casting through 3D Printing

Extreme recycling, in which nearly everything you own can be re-created as desired, is still in the future, but additive manufacturing is already being used to create customized durable goods and tools for use in traditional manufacturing facilities.

Because inexpensive plastic resins enable an amazing level of detail, 3D printing can capture intricate designs with precise details. These models can also be used to create precise master molds for limited runs of injection-molding bulk goods.

The benefits of digitally fabricating items include

- » **Flexibility:** Individual molds can be re-created as multicavity molds by creating multiple copies of the base design several times in the computer model and then printing a new model, with updates that improve corner-radius issues or add channels to increase flow efficiency.
- » **Repeatability:** As molds slowly degrade (with the softening of the sharp edges, for example), new molds can be created even years later, perfectly reproducing the originals.
- » **Scalability:** Digital designs can be printed at any scale, allowing manufacturers to create precise duplicates at half-scale or double-scale, as well as duplicates that include specific distortions to facilitate brand identification or enable artistic manipulations.

Lost-material casting

3D-printed materials such as thermoplastics and extruded wax designs can be used for lost-material casting, a process that's commonly used to create precious-metal jewelry. After the final design is created in a computer, the object can be printed with additional material to form basins, sprues, gates, and runners as a single object. This object is embedded in casting clay. When the clay has set, the cast mold is heated, allowing the plastic or wax to burn out and evacuate the casting mold cavity.

Sintered metal infusion

Manufacturers can make artistic metal objects by sintering inexpensive granular material such as steel into solid form. Because sintering doesn't involve complete melting, the resulting object is a porous mesh of steel particles bound into the desired shape. The object may be quite fragile, depending on the technique used to sinter the granular material. Embedding these objects in casting clay allows the introduction of a more artistically desirable material (such as bronze) into the mold, filling the void defined by the steel granules. After polishing, the resulting metal amalgam can produce an alloy with desirable artistic or material traits. Such processes can bind materials with dissimilar properties — impossible in traditional alloy injection molding.

Applying Artistic Touches and Personalization

The ability to create one-off designs makes it possible to create designs customized to individual characteristics and preferences, including manufacturing details such as logos and serial numbers that are fashioned into the object itself. This type of customization isn't possible in traditional molding, casting, or forging processes.

Medical implants

Perhaps the most specialized application of additive manufacturing is the creation of medical implants, which must fulfill a function while performing in harmony with the organic structures of the body (see Figure 3-9).

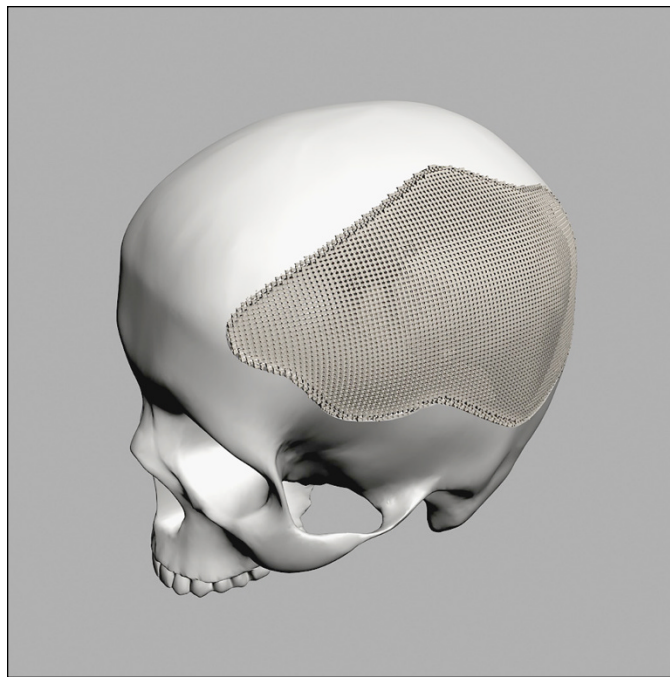


FIGURE 3-9:
A custom
3D-printed
cranial-flap
implant with a
porous structure.

Image courtesy of WithinLab

3D printing is limited only by the size of an object. Thus, the object's interior geometry can be solid, hollow, or complex. Objects can be created quickly, with optimum balance between strength and weight and minimal materials cost and

waste. Metals are often used in medical implants because they're not reactive to the body's natural processes. Titanium is popular but has such a high melting temperature that most designs are cast as solid models. This approach is costly for the patient and raises the possibility of postoperative damage from vibration and movement of the implant against biological materials such as bone.

Figure 3-10 shows a titanium artificial hip implant created by a 3D printer via selective laser sintering (SLS). This implant's highly complex metal geometry allows bone to grow into the implant itself, forming a bond that's much stronger than traditional screws and adhesives can provide.

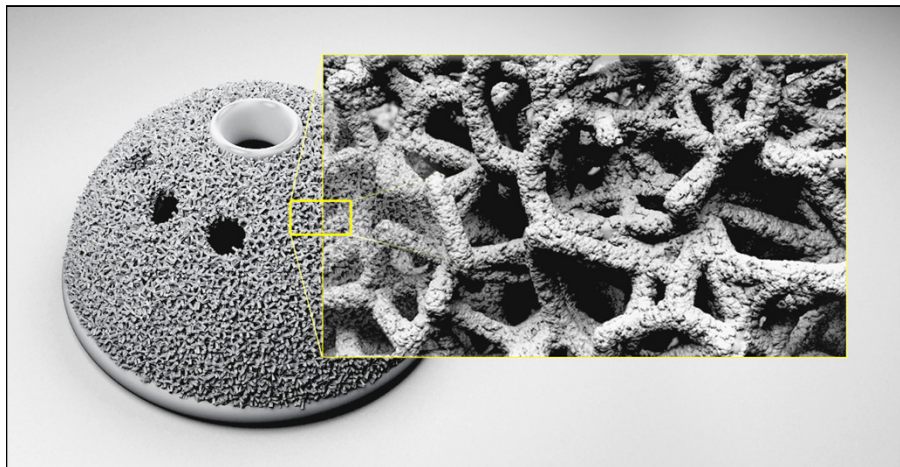


FIGURE 3-10:
An acetabular cup pelvic implant with complex metal lattices.

Image courtesy of WithinLab

Biological implants (organs)

3D printers can print materials other than plastic and metal, of course. Biological scaffolding materials can be used to print structures that can assist the growth of cells into replacement organs and tissues that can be implanted without rejection. These implants can be fabricated from the recipient's own stem cells, so no rejection occurs, and a perfect match is made with the patient's unique biology.

Item personalization

Personalization isn't restricted to material objects such as cellphone cases. A far more specialized application is biological prosthetics for reconstructive purposes or for replacement of missing limbs.

After a patient suffers massive facial injury, for example, 3D printing can re-create that person's features from old photographs or via modeling based on remaining body elements. This technique can return the ability to eat and drink normally to people who have suffered facial injuries or diseases. It can also provide a new ear for a person born with a functional inner ear but no external ear. Researchers are using 3D bioprinters to test bioengineered ears, using collagen and living cells to form a new structure that can be implanted to restore proper function.

External prosthetics have traditionally been little more than solid forms with as much articulation as their designers could provide. For example, one company creates custom coverings, called *fairings*, designed by creating a 3D model from a scan of the remaining limb. By mirroring the existing limb, the design integrates artistic designs with a balanced appearance created by an artist working with the recipient. Fairings can be created in plastic, or even chromed metal, using 3D printing to create a look that fits the recipient's unique personalized preference. (See Figure 3-11.)



FIGURE 3-11:
A personalized
prosthetic fairing
that mirrors the
remaining limb.

Clothing and textiles

Artists are developing new materials such as 3D-printed artificial leather and flexible lattices for use in clothing and footwear fitted to the recipient's form.

Designer Michael Schmidt and architect Francis Bitonti teamed up to create a 3D-printed gown custom-fitted to fashion model Dita von Teese, as shown in Figure 3-12. This dress was created from a curved latticework design based on the Fibonacci sequence, a mathematical relationship that defines many of nature's most beautiful shapes. Applying the lattice to a scan of the model's body allowed the creation of a 3D-printed mesh complete with interlocking flexible joints.



FIGURE 3-12:
A 3D-printed
gown.

*Image courtesy of the Francis Bitonti Studio (designer Michael Schmidt,
architect Francis Bitonti)*

The designers added Swarovski crystals to enhance the gown's appeal on the catwalk, but advances in multiple-material printers may make that treatment unnecessary in the near future. If this technology becomes more common, customers will step into a scanner and select the desired material to create custom-fabricated, 3D-printed pants that won't bunch at the waist or fall down on the hips.

Customizing Designs on the Fly

Almost any design for an object or device can be customized. Many times, issues are discovered only after a design is in use, which can prove troubling when the manufacturing facility is unavailable or far away.

Military operations

Navies operate ships for extended periods far from land, and these ships sometimes need parts or modifications that aren't readily available. Some ships employ onboard additive manufacturing systems for prototyping modifications and fabricating components.

Eventually, additive manufacturing will allow in-place repairs of equipment that currently can't be done outside a service yard. Metal cladding, for example, can use this process to add material to an existing metal object, allowing damaged or corroded mechanical equipment to be repaired. Submarines may be equipped with specialized 3D printers that crawl along the spaces between the inner and outer hulls, making repairs that are currently impossible.

The U.S. Army created the Mobile Expeditionary Lab, a 20-foot shipping container packed with rapid-fabrication systems that can be used by soldiers in the field who don't have access to parts shops and metalworks. Early successes of this lab include creating new brackets to make equipment fit on local vehicles and small covers that prevent soldiers' flashlights from being turned on accidentally during maneuvers. Bringing this capability to the location where the object is being used makes it possible to identify needs and test designs that fit the locale (a desert, say, as opposed to a jungle). Currently, the Army can get a new product, component, or update into use within days. Designs created at the lab are uploaded to a location where they can be reviewed, updated, or sent for full-scale fabrication, shortening the supply chain between the troops and their gear.

Space

Few environments provide a greater challenge than in space. If the only wrench that fits a spacecraft's radio mast gets lost during repairs, for example, it's exceptionally difficult to have a replacement delivered. No wonder NASA, SpaceX and other global space agencies are investigating and now using additive manufacturing. Being able to make what astronauts need in flight and en route, using basic materials and a 3D printer that can work without gravity or in a vacuum, is potentially a vital feature of future spacecraft and space travel.

The cost of lifting anything off the Earth is still (pardon the expression) astronomical. For missions to other planets, the use of native materials such as lunar soil and solar energy will be very appealing. As discussed earlier in this chapter, we're already able to use sand and dirt in additive manufacturing. If we can adapt the same systems used here on Earth so that they can be used on the moon, then we can send robotic systems ahead to print out roads and structures from regolith (moon rubble) to accommodate our astronauts without further costs for lifting materials to orbit and to the escape velocity beyond that.



Outlining 3D-Printing Resources

IN THIS PART . . .

Survey the various 3D-printing materials, including thermoplastics and nylon, liquid photopolymers, and dry granular materials for metal and ceramic objects.

Explore several different methods to create or capture 3D models, including scanning, designing in CAD software, and photogrammetric shape extraction using multiple photographs.

Check out the possibilities in bioprinting, which may allow us one day to print food, animal products, and even living tissues and organs.

Review the places you can find 3D-printable objects, such as Internet sources, virtual communities, and online repositories.

IN THIS CHAPTER

- » Understanding extruded materials options
- » Exploring granular materials options
- » Getting to know photo-cured resins
- » Exploring bioprinting
- » Examining other uses

Chapter 4

Identifying Available Materials for 3D Printing

This chapter provides an overview of many different materials for both industrial and desktop (consumer) 3D printing and helps explain how appropriate they are for handling and use. Although 3D printing is still in its infancy, the materials available are rapidly expanding, with new options becoming available almost every week. In the final chapters of this book, I describe how you can select, set up, and operate a 3D printer that uses melted plastic filament to fabricate solid objects as that's an appropriate material for the desktop 3D printers I highlight in later chapters.

The specific type of thermoplastic used for 3D printing determines the temperature that must be used to melt it. Melting temperature, in turn, has an effect on the strength of the final object and the type of surface needed to let the first layer hold properly through the printing process. In a 3D printer, only the final stage of the extruder heats up, with the filament remaining at room temperature until it reaches the fused filament fabrication (FFF)/fused deposition modeling (FDM) extruder's hot-end.



In your journey with 3D-printing materials, you may start to see the term *glass transition*. This is an indication of the useful maximum operating temperature of a thermoplastic. For example, PLA has a glass transition of around 60° C; at this point, the material is starting to be quite susceptible to heat and will very slowly start to deform (that is, “creep”). Glass transition is not the melting temperature; for PLA this is around 160° C; and most 3D printers extrude PLA at 200° C (or follow your material guidelines). If you placed a PLA printed part in your dishwasher for cleaning, it’s highly likely to deform, whereas a thermoplastic with a higher glass transition temperature such as PETG is much less likely to be damaged during the hot water exposure of a dish-washing cycle.

Ambient air temperature can affect the final product’s quality, with some professional printers heating an enclosed *build volume* (the maximum space in which a 3D printer can fabricate solid objects) to help each new layer bind more completely to the previous layer. The build plate can be heated in some printers to help the first layer adhere to the plate and limit warping, but the build plate can also be covered by a material to assist the plastic’s grip. Some types of filaments use common painter’s tape to assist first-layer adhesion to keep the object in place during the print process; other types of filaments may need a more exotic material, such as the heat-resistant polyimide Kapton tape that DuPont developed for NASA’s spacesuits.

Other materials are commonly used to help the first layer bind properly, including Acrylonitrile butadiene styrene (ABS) cement, hairspray, glue-stick, and even scrap filament dissolved in a compatible solvent and painted on the build plate to create a thin film. The materials simply need to be compatible with the thermoplastic being used.

For other types of 3D printers, layer binders may be present in the process itself (stereolithography [SLA], for example, binds the liquid to the build platform as it’s solidified), or they may be unnecessary, as in granular binding, in which the unbound powder stabilizes the object during printing. The techniques for securing a printed object in the first layer mirror the types of materials that can be used in the object’s fabrication, with different material types available for different techniques of fabrication.

Exploring Extruded Materials

As I discuss in Chapter 2, fused deposition modeling (FDM) systems such as RepRap 3D printers (which I discuss in Part 5) use extruded materials such as melted thermoplastic to create objects. Although thermoplastics are the most common types of filaments, new types of filaments become available every day.

Filament can generally be obtained as spools of plastic with a 1.75mm or 2.85mm diameter. Whatever size you choose, just be sure that the material itself is of sufficient quality. Many failed 3D prints can be directly attributed to flaws in the filament, such as the following:

- » Lower-quality filament manufacturing processes can result in filament being spooled while it's still slightly moldable, which may flatten it into an oval.
- » Filament extruded in varying thickness can distort the object being printed.
- » Dirty filament can drag impurities into the extruder, causing nozzle clogs and machine damage.

I would highly recommend using a quality filament like the examples shown in Figure 4-1. Other brands and materials that come on either cardboard spools or multi-use quick-fit spools will often help to indicate that the manufacturer is also working to lower the large levels of single use plastic waste that all too often still uses a traditional plastic spool. Cardboard spools work well and are much easier to recycle, often have a lower overall weight (helps shipping costs), and do help remove another source of single use plastic waste.



FIGURE 4-1:
Spools of thermoplastic filament of various materials supplied on sustainable cardboard spools.



REMEMBER

Professional-grade (and a few proprietary consumer-grade) 3D printers work only with filament in prespooled cartridges. Although such filament is more carefully quality-controlled and protected by the cartridge casing, these cartridges carry a higher price and provide fewer options than generic filaments.

Thermoplastics

Thermoplastics make up most of the types of filament used in FDM processes. Filament made from these thermoplastic materials can be created in many colors or as composite-filled materials. They can even be made to be transparent, glow-in-the-dark, or UV reactive.



TIP

Variations in the material qualities of filament types create difficulties if you decide to change from one filament type to another during a single print. Even so, halting a printout in the middle to change the color of filament is a common way to enhance the attractiveness of the final product. Figure 4-2 shows a 3D-printed puzzle bolt that makes use of paused printing by adding the nut to the bolt as it's being fabricated.



FIGURE 4-2: A 3D-printed puzzle for children includes a printed nut added to a dual-ended bolt paused during fabrication and then completed.

Thing #13923 at the Thingiverse repository, shared under the Creative Commons license by designer Aeva

Polylactic acid (PLA)

One of the most common thermoplastics in 3D printing is polylactic acid (PLA), an environmentally friendly, biodegradable polymer created with fermented plant starch from crops such as tapioca, corn, and sugar cane. This material can be printed on a print bed covered with painter's tape and doesn't require a heated build plate. PLA melts at a low temperature (around 160° C), although it bonds better around 200° C. Most PLA printers direct a small fan at the extruder to cool the material as it's added, preventing the hot-end of the extruder from remelting the previous layers.



TIP

PLA can be more brittle than other thermoplastics, although specialty versions are being developed for increased flexibility and a reduced carbon footprint during the material's creation. PLA is popular in cash-poor areas of the world because it can be created from whatever natural plant starch is available locally, very often from corn or potatoes. PLA is used to create rain-collectors and pipe fittings in many less-developed parts of the world, along with simple sanitation products such as toilet seats. It's somewhat more brittle than acrylonitrile butadiene styrene (ABS) and less flexible than nylon.

Acrylonitrile butadiene styrene (ABS)

Acrylonitrile butadiene styrene (ABS) plastic is used in a variety of industrial applications for extrusion and injection molding, such as the popular LEGO bricks. Its properties are well known, and the quality of filament can be easily controlled during manufacturing. ABS has the following qualities:

- » Melts at a higher temperature than PLA (150° C) but bonds better at 220–225° C
- » Extrudes more easily than PLA, with less friction as it passes through the extruder
- » Can be printed on Kapton tape or a thin layer of ABS cement
- » Proprietary glues can be applied to the build plate to help ABS and other thermoplastic bond the first layer to help reduce warping.
- » A slightly modified form of ABS called ASA (acrylonitrile styrene acrylate) is also becoming more commonplace for 3D printers. ASA can be easier to 3D-print and may often have improved mechanical resistance and higher heat deflection properties.



TIP

ABS plastic shrinks as it cools. Thus, a heated build plate produces better results by limiting the contraction of earlier layers to help reduce warping of larger objects.



WARNING

If used in a confined area. ABS has a mild odor during extrusion that can affect chemically sensitive people (and birds). ABS is also said to produce more airborne microscopic particles than PLA does. Without adequate air filtration it's generally less pleasant to use; it can also be trickier to print large objects exceeding 150mm due to its tendency to warp.

Polycarbonate (PC)

Polycarbonate (PC) materials such as Lexan are recent additions to the available thermoplastics used in 3D-printer filament. Because of PC's high resistance to scratches and impact, common applications include CD and DVD media as well as automotive and aerospace components. Greater strength and durability, however, require extruder temperatures of 260° C or higher, which some printers can't sustain. Although PC plastics are used in the creation of bulletproof glass when poured into forms, the layering in 3D printers creates microscopic voids between layers, so the final result isn't as strong as molded industrial equivalents. PC objects can also undergo a change in state when exposed to ultraviolet light, becoming more opaque and brittle over time. Formulations of PCABS and other blends of PC+ materials are also now available, making it easier to 3D-print and often lowering the required print temperatures.

Polyamides (nylon)

Nylon filament is another recent addition to 3D-printing options, especially useful for objects that require flexibility and strong self-bonding between layers. Nylon thermoplastic filament requires extrusion between 240° and 270° C and has excellent layer adhesion. Nylon is resistant to acetone, which dissolves materials such as ABS. In addition, polyamide materials can be opaque, transparent, or dyed different colors with common clothing dyes meant for nylon fabrics. Nylon can produce good flexible vessels such as vases and cups because its excellent layer bonding aids in the creation of watertight objects. My "tie-dyed" nylon filament (see Figure 4-3) allows for the creation of unique objects with color combinations along the length of a filament without requiring splicing or halting print jobs in the middle. This option is a popular one for hobbyists doing 3D printing at home, because clothing dyes are easily available.

Polyvinyl alcohol (PVA)

A popular option for water-soluble support is polyvinyl alcohol (PVA), a biodegradable industrial adhesive material extruded between 180° and 200° C. Some varieties of PVA are conductive and can be used to 3D-print electrical circuits directly into fabricated objects. PVA-printed material dissolves easily in water, however, so it must be isolated from atmospheric humidity. PVA is commonly used as a support material for other types of thermoplastics so that it can later be dissolved in water to reveal the final plastic object.

FIGURE 4-3:
A dyed nylon
3D-printed object
from Richard's
experimentation
with off-the-shelf
clothing dyes.



High-impact polystyrene (HIPS)

Another soluble support material is high-impact polystyrene (HIPS), a variation on styrene, which is the material used in packing material and food containers. HIPS has similar properties to ABS but dissolves in limonene (a biologically derived solvent made from citrus plants) rather than acetone, like ABS. HIPS filament is relatively new, and its use is still experimental, often messy and smelly. Like PVA, HIPS is used primarily as a soluble support material in combination with other types of thermoplastics.

High-density polyethylene (HDPE)

High-density polyethylene (HDPE) is the thermoplastic material used to create bottles and other recyclable items marked as No. 2 using the Society of Plastics Industry (SPI) scale. Because HDPE is common in recycle bins and in landfills, the use of HDPE scavenged from recyclables such as milk jugs is generating interest. HDPE binds easily to itself but has difficulty binding to other materials, so it often requires the use of an HDPE sheet as the build plate. Because it's relatively difficult to work with, HDPE isn't yet as popular for 3D printers, but its sheer availability as a byproduct of many industrial applications is encouraging efforts to use this material in additive manufacturing, especially as home filament extruders are now becoming more available.



Students at the University of Washington used extruded HDPE to create boats for a local milk-jug regatta competition and recently won a contest to use recycled HDPE in 3D printers to fabricate toilet seats and water-collection components for Third World areas. The sheer variety of containers fabricated using HDPE makes this material ideal for recycling in many parts of the world, allowing one nation's trash to be recycled as useful products when techniques for adapting recycled HDPE to 3D printing become more mature.

Polyethylene terephthalate glycol (PETG)

PETG is in the polyester family and is rapidly becoming the go-to alternative to ABS in 3D printing. PETG has a higher glass transition temperature and an extrusion temperature of around 235° C. It's usually compatible with any 3D printer that can use PLA and offers a higher impact resistance. PETG, however, is not quite as rigid as PLA but it does have more desirable print qualities such as a much lower tendency to warp than ABS. For some applications PLA can still be more suitable if rigidity is required. PETG is now most often used for the 3D-printed parts that make up a desktop 3D printer. If you ever have to replace a plastic mount, bracket, or guide on your own 3D printer, it's more likely to be made from PETG, and the replacements should also be printed from PETG. PETG can also be clear, translucent, or opaque and has some similar properties to nylon along with being more rigid than most nylons. PETG is probably one of the best complementary materials to PLA. If you only try out a few materials, do experiment with PETG over struggling with ABS or ASA.

Experimental materials

3D printing has brought with it a steady influx of new materials, including multiple variations on PLA, PETG, and ABS with new qualities and capabilities. PLA varieties include some that produce specific smells in the final printed objects. ABS alternatives include glow-in-the-dark and color-diode materials that shift colors in response to temperature variation (as 1970s mood rings did). New PETG-based products include carbon-fiber composites that provide for added rigidity as well as graphite or graphene conductive 3D-printable material suitable for embedded electronics applications.

A whole class of carbon-fiber composite versions of many of the established 3D-printing filaments now has widespread availability, such as PETG-CF, PLA-CF, PA-CF (nylon). Carbon fiber strands of varying lengths can add to rigidity, and in the case of materials which tend to contract and curl up such as ABS/ASA, can even make them easier to print.

However, many of these composite materials are abrasive, and will rapidly wear away the brass nozzles standard on most basic printers, and so require more specialist hardened nozzles to print – these are also now widely available for most printer brands as discussed in Chapter 14.

Composite materials can provide results that at first glance appear to be natural. An example is the use of wood fibers in WoodFill or Laywood-D3 filament, which produces an extruded solid form that can be sanded and painted like real wood. Varying the temperature of the extrusion during printing allows layers to blend darker and lighter regions to create grain-like patterns in the final objects. German researcher Kai Parthy has created new materials that result in sandstone-like appearance for architectural modeling, as well as extruded objects that are ductile and transparent — suitable for use as home-printed light pipes embedded in 3D-printed objects.

The Walt Disney Co. uses 3D-printed light pipes made of transparent 3D-printed plastics in its Printed Optics program (see Figure 4-4) to bring low-voltage, cool LED illumination directly to displays in ways that traditional incandescent-bulb designs simply can't match. The Printed Optics program is developing this technology to make toys more responsive to children, adding responsive elements to traditional components of Disney's theme parks. The printed optics provide illumination using low-power LED bulbs more individually fitted to specific purposes within Disney's array of exhibits.

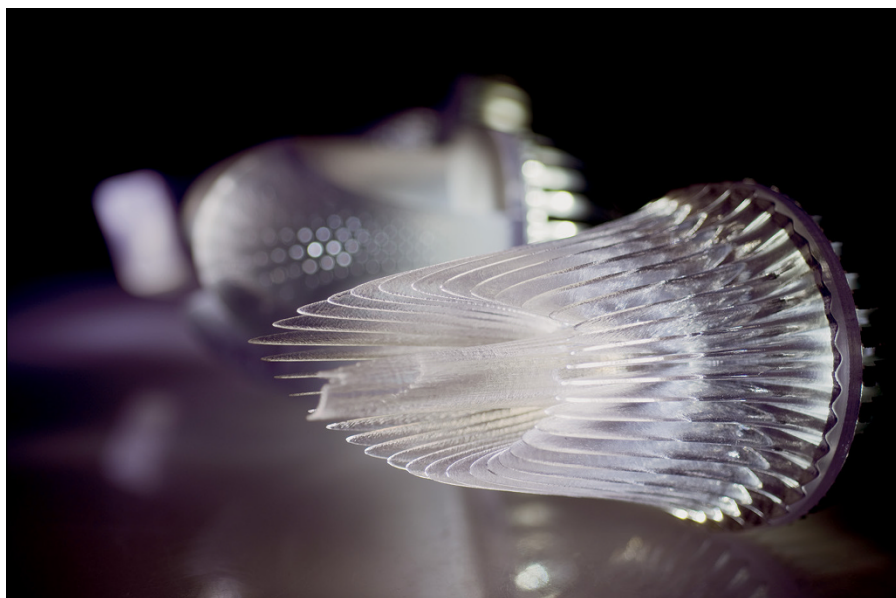


FIGURE 4-4:
3D-printed light
pipes used in
Disney's Printed
Optics program.

Image courtesy of The Walt Disney Co.

Extruded alternatives

Other options for 3D printing include pastes, gels, clays, and clay alternatives such as Play-Doh. The Hyrel3D printer can extrude objects made of air-dry clays and plasticine, using a proprietary screw-drive emulsifier. The open-source Fab@Home 3D printer, initially developed by students at Cornell University's Department of Mechanical & Aerospace Engineering, can create customized foods and other products from almost any material that can be puréed and squeezed out of a syringe, from cake batter and bread dough to printable scallop and celery pastes.

The RepRap printers that I discuss in Part 5 can use my open-source Universal Paste Extruder to create 3D-printed muffins, corn chips, and even chocolates like the bunny shown in Figure 4-5.



FIGURE 4-5:
3D-printed
white-and-dark
chocolate bunny,
created with a
RepRap 3D
printer and
Richard's
Universal Paste
Extruder.

Other alternatives use fused filament fabrication (FFF, which is another term for the proprietary term FDM, which is owned by Stratasys Corp.) with wax and granular materials in paste form such as sugar, salt, and some ceramic powders that are compatible with sintering and granular binding fabrication.

Identifying Granular Materials

Granular materials are used in sintering, melting, and additive applications with binding glues. You can use them to create objects from a variety of materials, including glass particles, plastic powders, and various metals and alloys — almost any type of material that can be rendered into a fine powder or granular state.

Plastic powders

Commercial printers like the multicolor ZPrinter bind plastic powders by using a liquid-glue ink jet. To further solidify the resulting objects, postprocessing typically includes a dip in cyanoacrylate resin to fill the gaps between particles. Without the resin filler, these objects typically lack the structural strength of other forms of additive-manufactured products. The use of inkjet binders allows for color mixing that's not possible through other forms of fused or sintered production. Other printers, like the VoxelJet system shown in Figure 4-6, can use materials such as granulated plastic and fine sand.

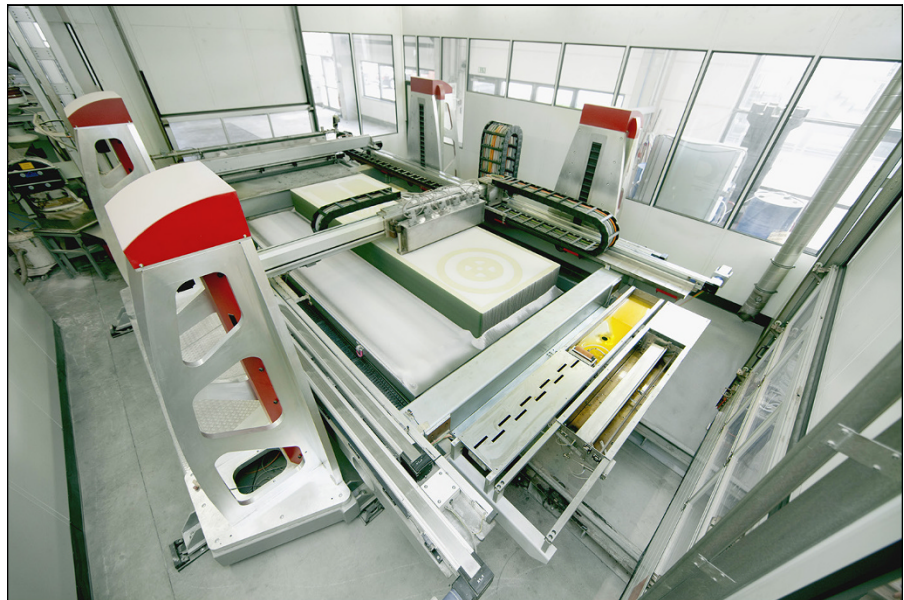


FIGURE 4-6:
The VoxelJet VX4000, which binds granular powder by using an overhead binder-application system.

Image courtesy of VoxelJet

Sugar and salt

Artistic uses for food-printed items include more than simple extruded chocolate. Granular binding of sugar and salt provides the fine control of details needed to

create complex structures like the sugar sculpture shown in Figure 4-7. Although sintering and melting of sugar granules is a way to fabricate objects, the application of heat caramelizes most sugars and creates color transformation during the process.

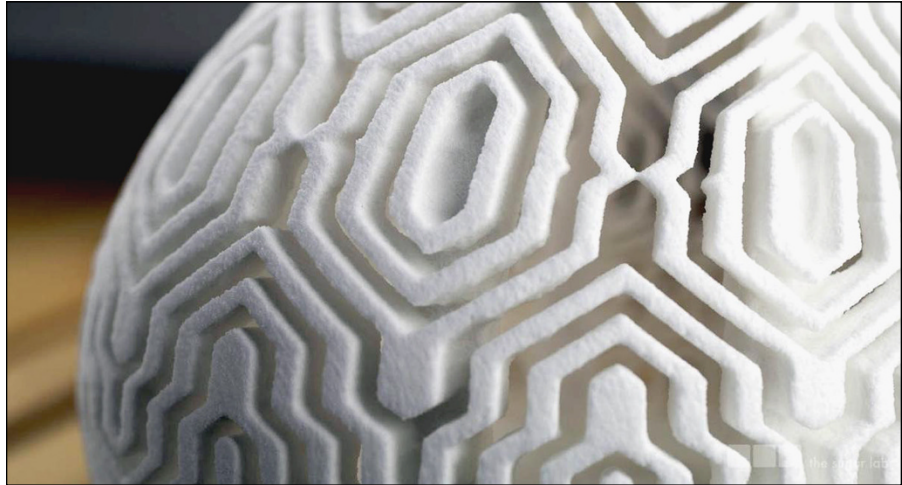


FIGURE 4-7:
3D printing with
bound sugar
granules.

Image courtesy of The Sugar Lab

Metal powders

Products for the aerospace, automotive, and medical fields require material much stronger than plastic — typically, biocompatible metals such as titanium or materials that can withstand very high temperatures or provide great strength-to-weight ratios for racing cars or aircraft components. Materials such as titanium and tungsten are difficult to use in traditional manufacturing because their high melting points and other factors prevent easy integration in traditional manufacturing techniques. Sintering and melting techniques using a laser or electron beam can result in very high-resolution details even when the materials don't alloy well or melt at matching temperatures. Figure 4-8 shows a granular binding of titanium particles done by sintering to create a custom medical implant.

Sand and natural granular materials

Silica and other minerals can be used to create items through additive manufacturing techniques such as granular binding, sintering, and melting the individual granules into an aggregate natural form of glass. Researchers such as MIT's Markus Kayser are exploring the use of naturally occurring sand, fused with sunlight, to create sustainable objects and structures in some of the poorest parts of

the world, where structural materials are costly and difficult to obtain. Figure 4-9 shows Kayser's Solar Sinter in operation, creating a rough, solid, natural-glass object from sand taken from the Egyptian desert without any further processing.

FIGURE 4-8:
Fine detail in
a titanium
joint implant
made with
metal powders
and an EOS
metal-sintering
system.



Image courtesy of Within Technologies

FIGURE 4-9:
Laser sintering of
granular sand
creates a rough
form of natural
glass.

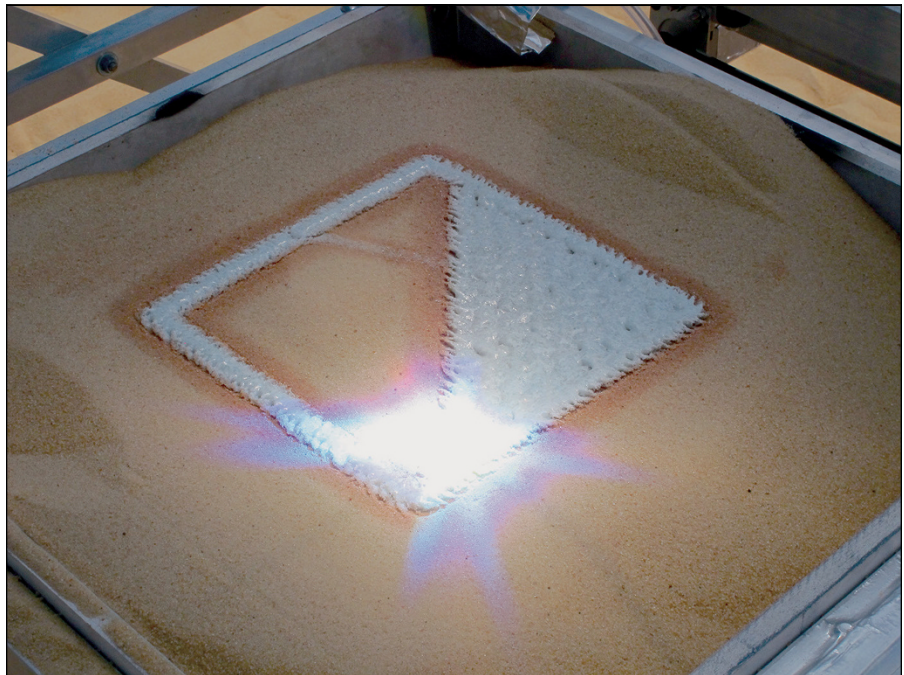


Image courtesy of Markus Kayser

Exploring Photo-Cured Resins

Photopolymer liquid resins used in stereolithographic (SLA) systems are so closely coupled to their particular applications that they're typically sold directly by the manufacturer to ensure compatibility. The resin's opacity affects how much light is necessary to cure a layer of the object being printed and how deeply each layer penetrates into the fluid pool. The frequency of light provided by the laser or Direct Laser Projection (DLP) projector affects absorption by the resin. In high-precision, multiphoton lithographic systems such as the NanoScribe (used to create the microscopic lattice shown in Figure 4-10), interaction among multiple illumination sources cures individual points within the build volume.

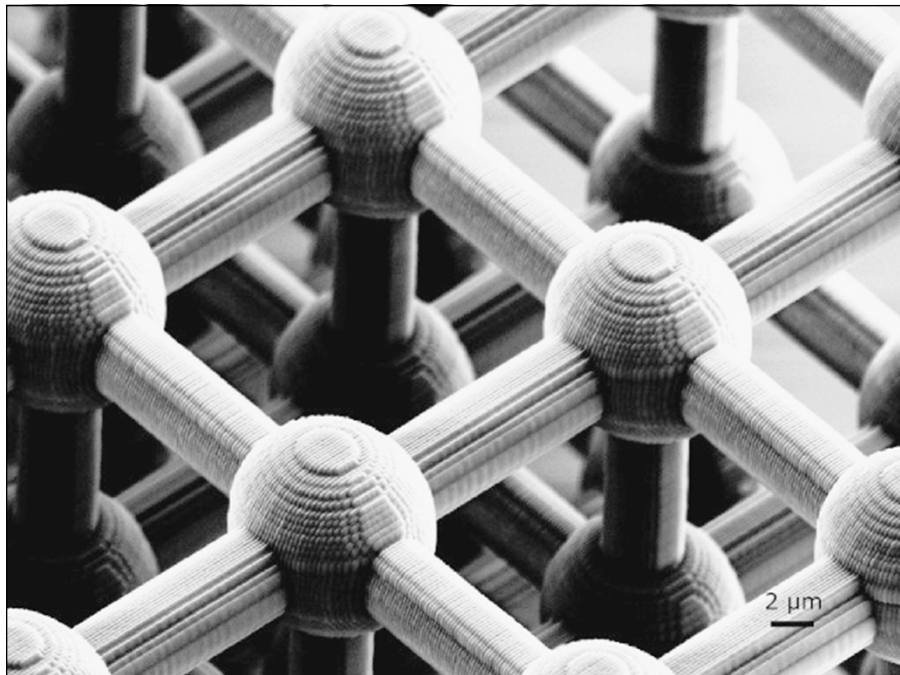


FIGURE 4-10: Photonic crystalline lattice created via two-photon lithography photographed through a microscope.

Image courtesy of NanoScribe

Understanding Bioprinting

Of all the types of additive manufacturing, perhaps the one with the greatest level of current interest is the capability to print living cells. The growing field of bioprinting may one day a) create picture-perfect, flavorful steaks, without the need

for methane-producing cattle farming; b) form leather clothing without the need to kill the original wearer of the skin; or c) fabricate replacement structures or even whole organs (see Chapter 3) from a patient's own cells rather than relying on organ donors. No generic bioprinting materials exist yet, and there are no standards for their use because this technology offers the potential to use an organism's own cells as the building blocks for more complex tissues and organs (refer to Figure 4-10).

Bioprinting food and animal products

Food sustains a population. In particular, proteins from meat require significant resources to produce — feed grains, fresh water, and land, in addition to the management of byproducts such as methane and animal waste from the farming of livestock. As the world looks to an ever-increasing number of hungry mouths, along with a dwindling supply of fresh water and open land, the ability to create edible tissues such as meat without the need for animals appeals both to economics and to the religious beliefs and/or preferences of much of the world's population.

POLYJET MATERIALS

In addition to creating liquid pools of photopolymer resins cured from the top or bottom of the pool by using external light sources, Objet Corp. (now merged with Stratasys Corp.) has created a different technique. Inkjet applicators apply the resins, and then ultraviolet light immediately cures the sprayed layer into a solid state.

This PolyJet application can mix materials in much the same way that traditional 2D printers mix ink colors, except that rather than mixing (say) blue and yellow to create green, the PolyJet printer can mix a flexible material and a rigid one to create objects with variable strength and flexibility. Complex areas with greater strength can be integrated with more flexible regions, all printed as a single object. Objects produced this way need no post-fabrication treatment with glues or other traditional techniques for assembly.

PolyJet printers allow use of the widest range of potential materials in a single print — currently, more than 104 options. By mixing materials, Objet can create a complete model ship in a transparent bottle or a medical model of a transparent body with only the significant details rendered as opaque objects.

Leather is another area under investigation, as there are many efforts worldwide to curtail the use of animals to provide fur, leather, and other bodily materials to use for clothing and other human purposes. Organizations such as People for the Ethical Treatment of Animals (PETA) have a growing interest in alternatives, but many parts of the world remain poverty-stricken and can't afford costly alternatives to traditionally manufactured shoes, cords, and animal-hide shelters. When bioprinted leather becomes available, this material could be used in a wide range of applications without harming a single animal and eliminating much of the cost and waste associated with farming.

Attempts to grow muscle tissue from 3D-printed gelatin structures and living cells aren't yet sufficiently mature to produce a sensibly priced steak or hamburger, but researchers are making significant progress along the way to truly viable lab-grown meat; this is only a matter of time and scale to make a reality. Several companies are attempting to create no-kill bioprinting alternatives to meat and leather production, using additive manufacturing techniques.

Replacement tissues and organs

Biological tissues can be used to repair or even enhance human bodies. Unlike donor tissues, bioprinted alternatives will be fashioned from patients' own cells, so antirejection medications and waiting lists for biocompatible matches will be relics of a bygone era. Early successes in bioprinted tissues and organs include blood vessels, tracheas, and bladder equivalents due to the simplicity of their cellular structure.

Organovo recently announced progress on a 3D-printed liver by merging several types of tissues in a complex structure that may soon lead to a 3D-printed replacement for the body's principal filter. Efforts to 3D-print heart and lung tissues may result in techniques that address common frailties brought on by age. 3D-printed biocompatible implants are already being tested for cosmetic and reconstructive purposes.



REMEMBER

These techniques also have potentially negative uses, of course. An athlete could be given additional muscle tissue or enhanced connective tissues merely to enhance performance. The ability to visit a bioprinting cosmetic surgery office to have a facelift that results in applying the current top supermodel's facial structure to your own could result in copyright-infringement lawsuits that currently seem bizarre.

National cultures and legal systems need time to adapt to the potential of these technologies to extend human life spans, to modify appearance, or to craft new capabilities.

Identifying Other Uses for Materials

Because additive manufacturing methods may be applied in almost every area of manufacturing and production, over time new sources of materials for 3D printing will be developed.

Recycling materials

As 3D-printed buildings become available in the form of extruded concrete structures, a more efficient approach to construction becomes possible. Elements such as power conduits and plumbing can be created directly within the structure itself during printing. Rapid assembly systems might create components on one side of a new building and assemble them on the other side while the 3D fabricator builds up one layer of concrete after another with the accommodations prefabricated for the other components. Recycled materials would be a natural fit for this process.

Artist Dirk Vander Kooij has taken the plastic from old refrigerators to create extruded furniture in his Endless line. Other inventors have been working on devices that home users can use to create new 3D-printing filament from inexpensive bulk pellets or even their old failed prints and waste thermoplastic materials.

Thus, additive manufacturing offers the chance to green the making of new materials and products in several ways, including

- » Reducing the need for materials in the initial manufacturing process by eliminating post-fabrication machining and waste-material cutoffs
- » Allowing the efficient creation of complex structures with interior voids that aren't possible in traditional casting or injection molding
- » Recovering and recycling materials for use in 3D printing

Such advantages will help realize long-term sustainability in the face of reduced resources in the post-peak-oil economy.



REMEMBER

Researchers are having early success in using recycled paper, glass, and pulverized concrete to create new material for additive manufacturing. In addition, more environmentally favorable materials are emerging, such as the fully biodegradable, plant-sugar-based PLA thermoplastic. As bioprinting continues to expand, new types of foods and other non-animal-based goods may become possible. These techniques won't require killing live animals or maintaining massive quantities of livestock with fresh water and grains that could be used by the ever-growing number of humans.

Sustainable large-scale 3D printing with local materials

WASP, the World's Advanced Saving Project (based in Italy) is a 3D-printer company with quite an impressive manifesto. (Check it out yourself at www.3dwasp.com/en/about-us/#manifesto.) The folks at WASP have already produced giant 3D printers that can construct clay houses, inspired by the construction technique of mason wasps to 3D-print walls and a roof made from local materials like clay and earth found in the surrounding area. Machines like this could be deployed to help rebuild temporary shelters after a disaster or to manufacture more permanent structures for long-term living.

Producing food

NASA is funding research on a 3D printer that can produce foods such as pizza from powdered basic materials that can be emulsified into pastes by using only water. The pastes would be extruded layer by layer and even cooked by the heated build plate of a 3D printer designed for long-term missions for exploring the solar system. The shelf life of such powdered foods would be 30 years or more, allowing the creation of food stockpiles that could be distributed as needed.

Caring for people

In the wake of a major catastrophe, a mobile additive manufacturing facility containing machines like the WASP printer described previously could provide food and shelter even as damaged structures and debris are collected and recycled into the material that will form replacements for all that was lost to the flood, earthquake, or tsunami. Injuries may be repaired using 3D bioprinters to create compatible tissue based on living cells collected from the injured, preventing issues of tissue matching or potential rejection.

In daily use, 3D printers may serve as custom formularies, creating courses of medications precisely matched to individual patients' needs. Instead of taking two pills of medication X each day for ten days and then one pill of medication X and one pill of medication Y in a particular course of treatment, a patient could simplify the regimen. Specialized 3D printers will soon be able to create each day's medications in the minimum possible number of pills, delivering the precise combination, dosage, and proportions of medications needed for each day's treatment.

- » Getting to know object repositories
- » Building designs
- » Creating scans of objects
- » Working with photogrammetry
- » Getting ready to print

Chapter 5

Identifying Sources and Communities for 3D-Printable Objects

3D printers are becoming commonplace in businesses, schools, libraries, and homes. Online services such as Shapeways, Ponoko, and i.materialise can transform 3D models into solid form, even if you lack a printer of your own. A model can be shared with people around the world as easily as a song in MP3 format or a photograph on a photo-sharing site. This chapter reviews several ways to create 3D models suitable for printing or sharing.



WARNING

Keep in mind, however, that not all object designs are intended to be captured, shared, or otherwise produced without the designer's permission. Before you create an object or sell a design of your own, make sure that it truly is yours to use. Chapter 11 discusses common licensing models used in the 3D-printing community. It's really important to stress that you should always use the creative work of others only as they request and as per the license terms used.

If in doubt, ask before you use! Creators often respond positively to polite up-front requests, whereas the community will often find and expose improper use of a creator's work.

That being said, you can easily find designs with few restrictions, such as those whose creators have stipulated only that their designs be attributed to them as the creators. You have a wealth of models to get you started in 3D printing!

Exploring Object Repositories

A virtual 3D object model is encapsulated in standard file formats, such as `.stl` and `.obj`. Individual 3D model files can be transmitted via email, stored in a repository, or shared on any other service that handles ASCII data. Software-specific file types require access to the proper software to open and manipulate the solid model. Other file formats for software that can be used to save and share 3D models online include `.skp` (SketchUp), `.sldprt` (SolidWorks), `.stp` (Autodesk 3DS Max), `.blend` (Blender), and `.dxf` (Autodesk).

Collections of these files are referred to as *repositories*. Repositories can be individual vendors' sites created to supplement their own products. (The Maker's Tool Works MendelMax RepRap design discussed in Chapters 11 through 15, for example, is shared at <https://github.com/Makers-Tool-Works/MendelMax-2.0>.) Repositories also can be open-source sharing sites such as MakerBot's Thingiverse or personal file-sharing services such as GitHub. (My Delta printer RepRap design, for example, is shared at my personal GitHub site, <https://github.com/RichRap/3DR-Delta-Printer>.)

Vendor repositories

Perhaps the first treasure-troves of 3D-printable designs that most people discover are the online repositories provided by vendors of 3D printers. When Prusa Printers sells a new 3D printer, the company wants to make sure that the buyer can download sample models to test the new printer and share their own model designs with other users also running either a Prusa 3D printer proper or a compatible printer.

In the case of Prusa Printers and Prusa Research, they host a 3D model file-sharing site called Printables.com; here, you can find free file downloads for a variety of 3D-printable objects, such as cases for your iPhone, buttons you can sew onto your favorite shirt, or jack-o-lantern decorations for Halloween fun. The platform provides free designs that you can download and modify with a variety of software applications (which I cover later in this chapter) and then print in solid form.



TIP

Printables.com offers a file-sharing website where users and designers can post models, projects, and even completed images of 3D-printed objects. It's now quite common to find the models of 3D-printed parts needed to build a 3D printer being posted on these file-sharing sites. Users will also enhance, upgrade, and generally improve models and share them so other users can enjoy the improvements.

With the ability to upgrade parts in 3D printers or other products with self-printed replacements, vendors can provide designs to enhance or personalize their products, as Nokia did with the 3D-printable phone case I mention in Chapter 1. The vendor increases the desirability of a product line by allowing consumers to design their own products or purchase designs provided by someone else that customers can print at home or through an online service.

This type of repository allows one to make mid-process modifications without requiring the reassembly of a packaged kit. Instead, consumers receive a notice of the upgrade and the location at which it can be downloaded.

Some vendors even provide designs to help customers repair their objects. In this way, vendors can work around an expensive product recall. Using a metal-fabrication system, for example, customers could print a repair in a matter of hours at their local 3D-printing center instead of waiting for weeks for a tiny replacement part to be shipped to their home. Other parts could be designed for fabrication in plastic on consumer-grade home 3D printers.

Community repositories

Another source of 3D-printable objects is the Internet. Users of online community repositories upload models for a variety of reasons — for educational purposes or artistic expression, for example, or in order to distribute functional parts such as the components of a 3D printer. Closely coupled with the Maker movement, these repositories generally support open-source designs and shared licensing models.

Many of the models that I use as examples in this book come from community repositories such as Thingiverse (www.thingiverse.com), Printables (www.printables.com/) and Youmagine (www.youmagine.com/), which were designed to hold open-source 3D design files and instructions. Figure 5-1 shows a few object designs from Thingiverse, which houses hundreds of thousands of downloadable models, both original and derivative. These object models are grouped into categories such as Art, Fashion, and 3D Printers. You can easily spend an afternoon browsing the lists of designs.

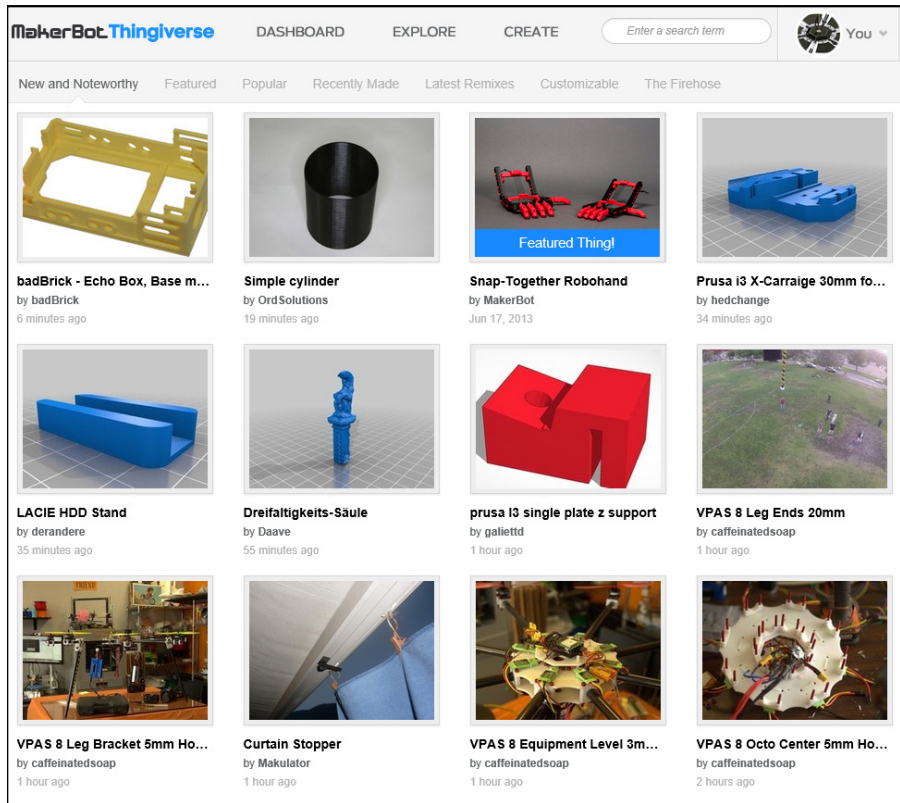


FIGURE 5-1: Example designs from the Thingiverse community repository.

Many upgrades for off-the-shelf 3D printers are shared via repositories. Plans for entire 3D printers are available there if the creators decided to share them as open-source designs. The 3D-printer kits that I describe in Part 5 can be constructed with downloaded 3D-printable object models and off-the-shelf components from local electronics and hardware stores. The kits eliminate the need to search for compatible components or materials you might have to fabricate yourself. Commercial repositories are great for getting first-time 3D printers up and printing quickly, but for self-built systems, kits save the time needed to track down unusual parts such as toothed belts and stepper motors.

Designing in the Computer

Until a few years ago, creating 3D models involved computer-aided drafting (CAD) software (such as Autodesk Revit, shown in Figure 5-2) that required powerful computers and expensive specialized software. For years, CAD was well beyond the capabilities of most people outside a dedicated group of specialists.

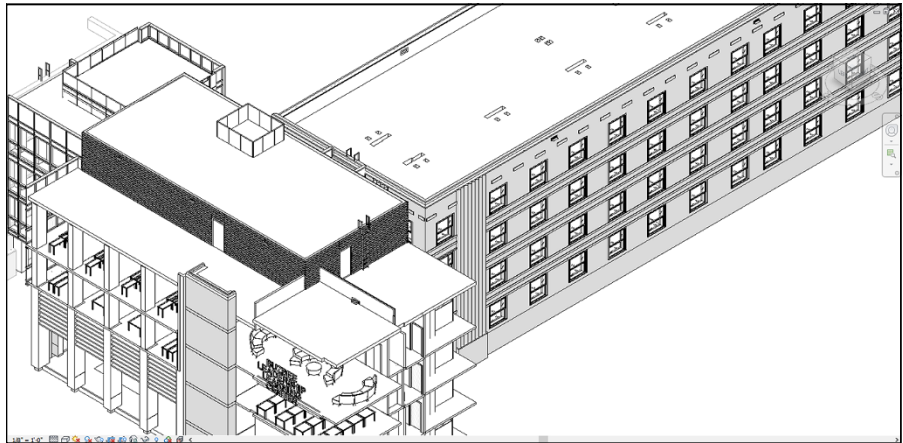


FIGURE 5-2:
A CAD design in
Autodesk Revit.

Additive manufacturing allows the creation of complex internal structures rather than simple, solid-block components — an improvement over traditional CAD tools, which can't always create models to match the true capabilities of 3D printers. New software tools are becoming available for specific purposes, such as medical implants that must be highly customized to fit an individual's bone structure while also allowing complex lattices and other forms of nonsolid structures. Figure 5-3 shows a complex structural lattice applied to what was originally a hollow sphere with sliced-off sides.

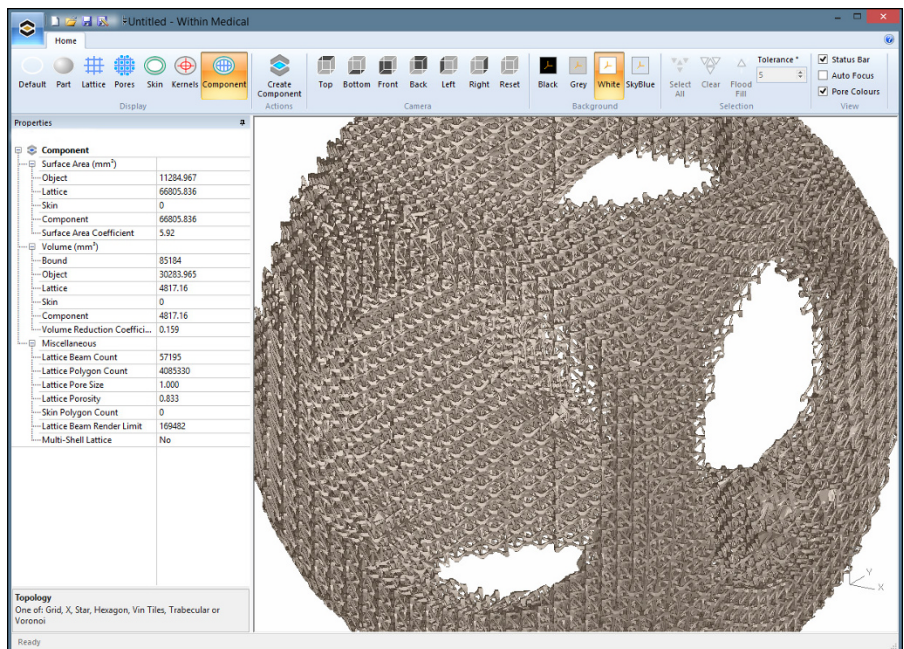


FIGURE 5-3:
A complex
latticework object
created with
Within Medical
software.

High-end and special-purpose CAD software requires extensive training and practice to use properly. Much more user-friendly, lower-cost alternatives have been developed for home users. Options include SketchUp and Blender. Public school teachers in the SOLID Learning program often use the browser-based TinkerCAD program (see Figure 5-4) because it's free and cloud-based, with a simple, easy-to-understand user interface.

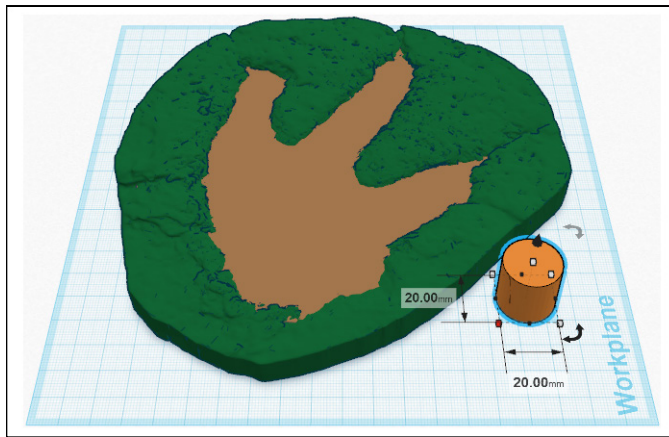


FIGURE 5-4: TinkerCAD being used to prepare a 3D-printable mold from scanned dinosaur tracks at the Glen Rose excavation.

Autodesk has released a series of free-to-use options for popular tablet devices. These apps rely on cloud-based processing instead of calculations done by the tablet device itself, so users can get an excellent result in little time.

Not all 3D-modeling programs require strict dimensioning and hard edges, because additive manufacturing provides a much more flexible build environment than traditional manufacturing for home designers. Another free application in Autodesk's tablet suite is 123D Creature, which has a simple drag-and-drop interface. (see Figure 5-5).

Many 3D design and modeling programs can export files into common 3D-printer formats (such as the .stl encoding I use in my RepRap examples in Part 5), allowing designers to use their favorite tools to build complex, beautiful work to print, share, or sell. 3D printing allows designers to sell their artwork and other designs directly to the public without the limitations of production in traditional manufacturing.



FIGURE 5-5:
A 3D monster
model in the
tablet-based
123D Creature
application.

Scanning Objects

You can capture objects on a computer so that you can modify or re-create them with a 3D printer. This capability is particularly useful in the case of artwork or other unique formations that could not otherwise be designed easily in a computer model. The Glen Rose dinosaur track shown in Figure 5-4, earlier in this chapter, came from a laser scan of the original fossilized impression, which was used to create an electronic copy (see Figure 5-6) of the track that can be shared without risk to the original.

Optical scanning captures only the outer shape of an object, but it's possible to use ultrasound imaging or computer tomography (CT) scan data to create models of internal structures as well. Researchers recently created a model of the first full skeleton of a living animal by 3D-printing the bone structure taken from a CT

scan of the subject. Similar data is being used to reconstruct the facial features of mummified remains in Egypt and of the newly discovered remains of King Richard III. Using CT scans and a stereolithographic system, researchers at the University of Dundee were able to print King Richard III's skull in solid form, showing what this long-dead monarch looked like in life.

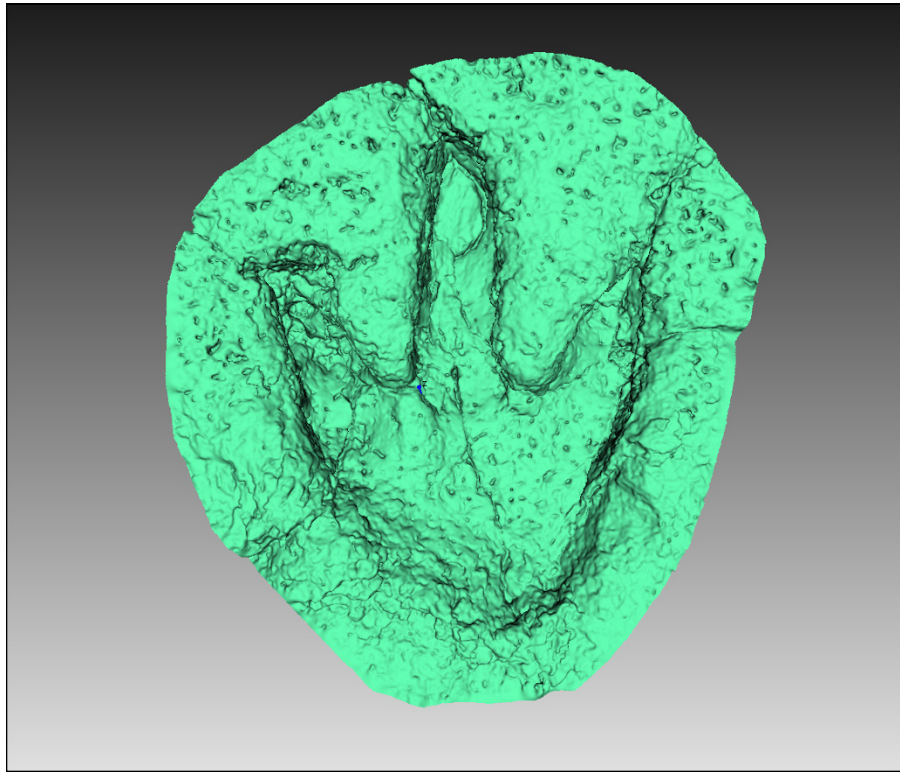


FIGURE 5-6:
A scanned virtual
copy of the Glen
Rose dinosaur
track.

Early 3D capturing systems relied on a probe that contacted the printed object at many locations, defining a point cloud around the object's shape to define its basic geometry, which was filled in with greater detail as the scanner measured finer points between the original markers. These systems are still used in machinery analysis and other durable environments. More recent scanners use illumination from lasers or *structured light* — projections that measure the distance from the camera to different parts of an object so that there's no risk of harm to the object from the contact points of the scanner. Figure 5-7 shows a handheld Einstar scanner being used to scan a water meter manifold (large water pipe fitting). Coupled with software on a computer, this structured-light scanner can build a 3D model from repeated measurements of an object's surface structure as the scanner is waved above an object of interest, or the object being scanned can be rotated on a platform to help capture all angles with the handheld scanner.

FIGURE 5-7:
A handheld
EinStar
structured-light
scanner being
used to capture a
water meter
manifold to be
used as a model
for 3D printing.



Modern structured light scanners costing around \$1,000+ use a combination of optical wavelengths to help see all the features on a target object; by projecting invisible lines of infrared light, the scanner lets you capture contours, edges, and texture data. (Shiny surfaces can be tricky to scan due to light being reflected directly back into the sensor, blinding the image.) Adhesive dots can be added to a large and complex model to assist with tracking features and scanning details correctly. (The completed scan shown in Figure 5-8 is the result of scanning all parts of the target model and then converting the point cloud data into a solid mesh model that can be 3D-printed.)

Commercial 3D scanners provide very high-resolution models of scanned objects. Such devices can be small handheld scanners or large, complex systems that map multiple angles at the same time. Scanners can image the inside surfaces of pipes, map mine shafts and subterranean caverns, and even scan entire build sites for large structures by using laser tools called LiDAR. Such systems can be used in mining operations to calculate ore removal and in surveying to create digital terrain maps.

Companies such as Creafom, FARO, Artec, and Shining 3D provide very high-resolution object models suitable for industrial applications and manufacturing. Figure 5-9 shows the 3D model scan from Figure 5-8 printed out as a smaller scale model. Support structures have been used to assist the 3D printer with overhanging features of the design; these will be snapped off from the finished 3D print after removal from the build platform.

FIGURE 5-8: Multiple scans can be joined together, resulting in a completed point cloud and finally a solid 3D model that can be 3D-printed.

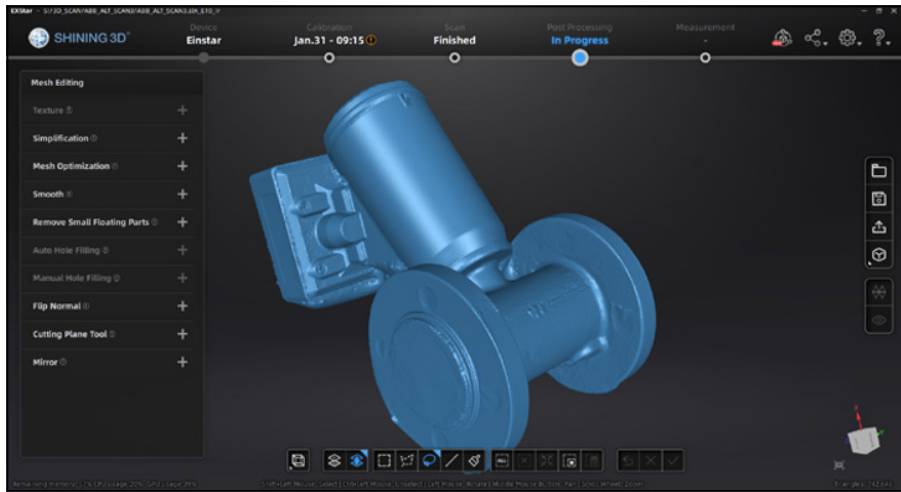
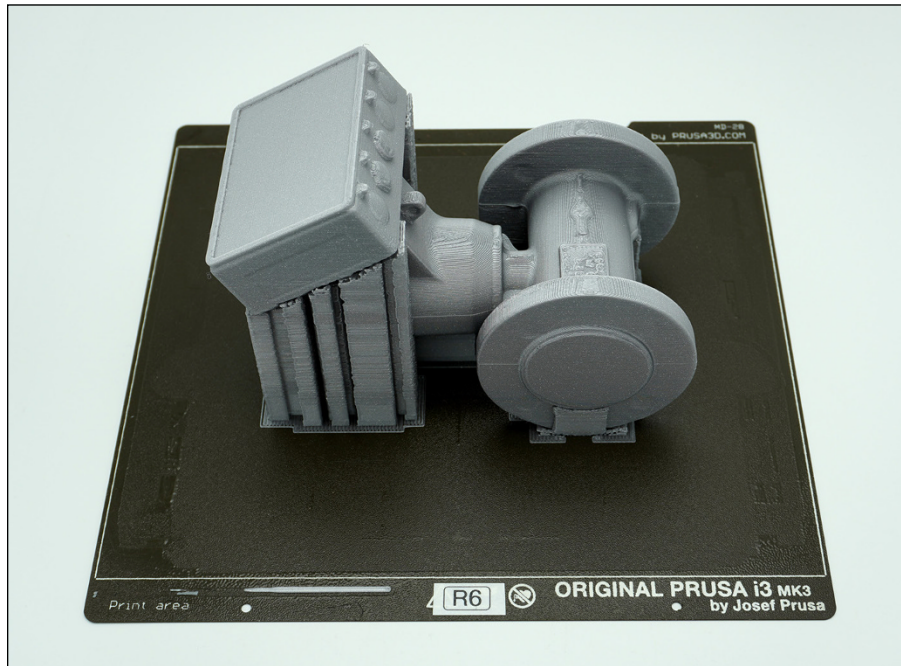


FIGURE 5-9: The scanned 3D model is printed at a smaller scale; support materials can be easily removed to reveal the completed 3D object.



Capturing Structure from Photographs

Very high-resolution modeling for computer graphics can be performed with 3D scanners, but capturing an object in motion, such as a runner leaving the starting blocks, requires another technique: photogrammetry. *Photogrammetry* uses multiple 2D photographs to calculate the shape of objects within the field of view. By taking multiple photographs at the same moment, this technique captures objects in motion as easily as the still objects required for 3D scanners.

Photogrammetric results are rarely as exact as scanned equivalents because all points are calculated based on differences between two photos taken at slightly different locations. Professional photogrammetric studios like the one featured in Figure 5-10 use carefully measured locations for each camera, as well as highly calibrated depth-of-field measurements on the lenses and lighting, to provide the best possible capture of living subjects. Models using systems like this can capture details down to individual hairs on a subject's arm, depending on the type of lenses and number of cameras used.

FIGURE 5-10: Photogrammetric studio using 110 Canon DSLR cameras synchronized by six laptop computers.

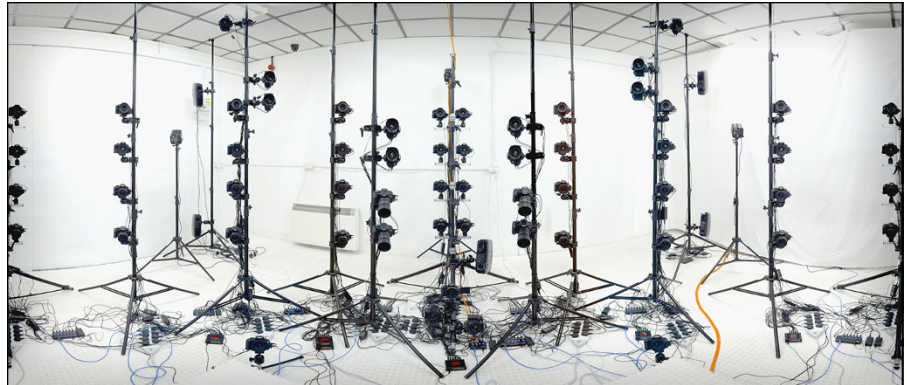
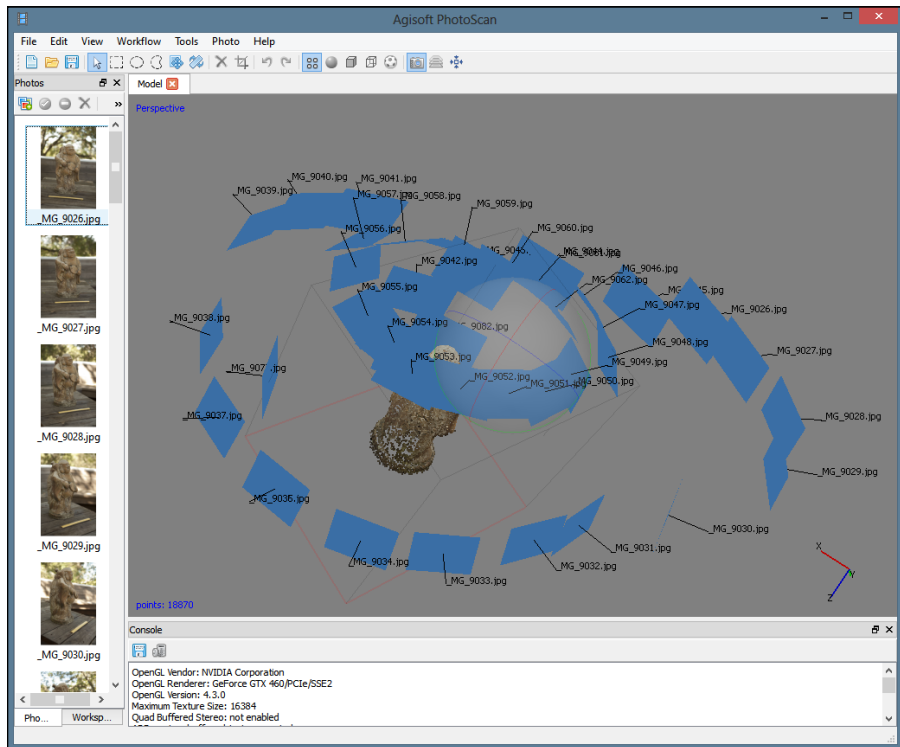


Image courtesy of Lee Smith/Infinite Realities

Advances in computing power, particularly in video card GPGPU processors, have made photogrammetry available to home users who lack high-end supercomputers. Some early outline structures from motion techniques have been collected in commercial software packages such as Agisoft's PhotoScan (see Figure 5-11), which is used to capture 3D models for movie computer graphics. Video game designers and artists use these programs to create full-body, full-motion captures of subjects.

As computing power increases, photogrammetric applications have developed greater capability to locate similar features in several photos and calculate the relative position of the camera for each photograph without the fine calibration needed for a professional studio.

FIGURE 5-11: Photogrammetry using PhotoScan to calculate an object from a series of photos taken from around the object.



Autodesk's free, cloud-based 123D Catch application allows tablet and PC users to perform photogrammetry even when their computers lack the resources to process all the details in a reasonable amount of time. Using an example photographic set, the model of a warrior's statue shown in Figure 5-12 was extracted using a standard home computer in little more than five days. The same translation can be made in just under three hours by using the Create 3D model feature built into the browser-based Autodesk 360 software.

Photogrammetric surface calculations can be used to capture 3D models of statues, moving people, and animals even when a high-resolution 3D scan wouldn't be quick enough to capture all the subject's details. The same systems can stitch together photographs to build models of buildings and even areas of land for agricultural review. By using a drone or other type of unpiloted aerial vehicle equipped with a camera, architects can capture a 3D model of a business park by flying the vehicle overhead and then building the model using photogrammetry techniques. Researchers in the field of marine archaeology are starting to use submersible vehicles to map wreckage and debris on the ocean floor so that they can plan recovery dives before anyone enters the water.



FIGURE 5-12:
A 3D model
created with
photogrammetry
and a series of
photographs.

Preparing Models for Printing

No surfaces of a 3D-printable object can have any holes, meaning they must essentially be watertight to print successfully. A hole *through* the object is fine, so a 3D-printed doughnut is possible, but a hole in the surface of an object must be filled or patched to create a continuous outer surface before printing. When a scanner calculates a 3D object's shape, it does so by using only the scanned surface (the outside), so minor holes and other imperfections may require additional cleanup before the design is complete.

Some models need repair before they're 3D-printed, whether they were created via CAD, scanned into a computer, or calculated from photographs through photogrammetry. Holes in the surface may need to be filled; misaligned faces may need to be resolved (because a model has only an outside without an inside, the results can be mixed up if two models intersect); extraneous details may need to be trimmed, leaving only the part you want to print. Figure 5-13 shows the warrior statue from Figure 5-12. This model required holes to be filled and the base sliced from the ground to provide a clean platform of the model to print.



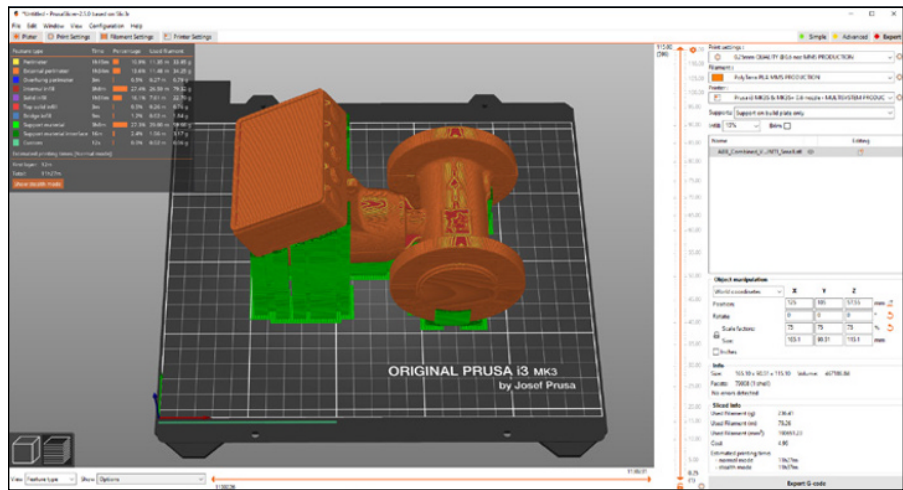
FIGURE 5-13:
The full 3D model
of the warrior
statue before
being cleaned up
and made ready
for 3D printing.

The model of King Richard III's skull discussed in the “Scanning Objects” section, earlier in this chapter, was prepared with the commercial Geomagic Freeform application, but free software tools are available to assist educators, home users, and hobbyists who are just getting into 3D printing. The following sections offer an overview.

3D model viewers

One of the most useful additions to your suite of tools is a 3D object viewer that you use to inspect your object before printing. The 3D printer's control interface uses this system to lay out items on the build plate before printing begins, but other programs can make selection between models easier. 3D models can be viewed in 3D-printer control software such as Prusa3D or Cura. The scanned 3D model then is prepared onto the build platform shown in Figure 5-14. Support material is automatically added to assist with printing the layered object.

FIGURE 5-14: The scanned 3D model is loaded into Prusa3D and sliced into a set of Gcode commands that the 3D printer then uses to build the model layer by layer.



Mesh modelers

Mesh is the term used to describe the surface of a 3D model, which is defined using numerous small triangles to define the surface. Many tools can export 3D designs in formats such as .ply, .stl, .obj, and .collada, and a tool such as the free, open-source MeshLab can convert these formats into the one your 3D printer needs. Other mesh modelers, such as the free Meshmixer from Autodesk, can either cut away the parts of a scan or photogrammetric mesh you don't want or close the holes in an incomplete mesh. Figure 5-15 shows the 3D scan loaded into Meshlab, a program that was able to reduce the vast amount of data of the original scan (more than 850MB) down to around 35MB to make editing and 3D manipulation of the model easier, along with a more convenient sized model to share online.

Mesh repairers

In addition to Meshmixer and MeshLab, several tools excel in creating a manifold object surface by extending a surface to fill gaps or overlapping areas where two manifold surfaces meet. One of the most common tools for accomplishing these tasks is Netfabb Studio, a commercial software program that also has a basic free version for noncommercial personal use. Such tools automate the preparation and repair of 3D objects — a handy capability for users who are new to 3D modeling.

After checking the 3D scan in Netfabb and loading it into the Prusa 3D slicing program as shown in Figure 5-16, the final 3D model was printed, and the support material was easily removed by hand. The final detail was to add a retirement celebration plate that was also 3D-printed. And the scale model was ready to be presented. (See Figure 5-16.)

FIGURE 5-15: Meshlab was used to reduce the massive model data by collapsing polygons to reduce overall size.

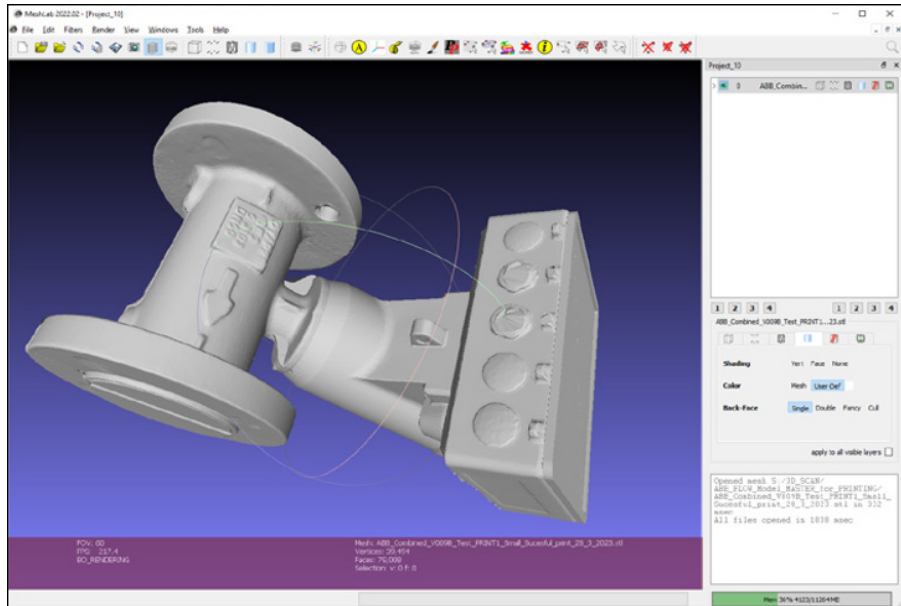


FIGURE 5-16: After printing, it's often necessary to remove support material from a model.





Exploring the Business Side of 3D Printing

IN THIS PART . . .

Find out how 3D printing is changing the world of business and manufacturing.

Consider the possibilities of using a design based on an expired patent.

Examine the ethics of additive manufacturing.

Explore the future of 3D-printed designs.

- » Making manufacturing widely accessible
- » Monetizing designs
- » Forging new paths in design
- » Making advancements in tool design

Chapter 6

3D Printing for Everyone

Beyond the ability to print items for personal enjoyment or use, 3D printing offers moneymaking opportunities that weren't possible even a few years ago. The earliest commodity application of additive manufacturing was in prototyping; its ease of one-off fabrication for testing earned it early fame as a rapid prototyping solution. Many products are tested by creating a physical model through additive manufacturing, allowing consumers to test fit (and tinker with) the arrangement of controls and mechanical features by using a model of the intended product. 3D printing still facilitates the creation of rapid prototypes of different designs, but its capabilities have expanded to include metal and ceramic materials suitable for the fabrication of durable production goods.

This chapter examines many of the emerging uses for additive manufacturing systems, which are already opening new industries for exploration and 3D printing for everyone.

Democratizing Manufacturing

Massive corporations such as Microsoft use additive manufacturing to prototype designs for their latest video-game controllers. Small businesses can try out new products that wouldn't have been possible in traditional manufacturing chains, skipping the multiple rounds of designers, sculptors, casting fabricators, and a host of other specialists and technologies well beyond the budget for small start-ups trying to break into a new market. 3D printing truly is democratizing the

production process by providing a mechanism by which any person can create a design on free software and then physically produce that idea all while still sitting at their computer.

The following sections discuss a few modern commercial applications of additive manufacturing.

Derived designs

3D printers capable of fabricating solid objects from metals and ceramics allow jewel crafters to design and create intricate pieces of jewelry. Small-volume production runs allow jewelers to make custom pieces designed to fit an individual client. Even people without skills in alloying or casting metals or other manufacturing processes can create new works. The flexibility of 3D printers means that you can create an original design in the computer or by mixing elements of other designs to create a new design for fabrication.

Many designs merge 3D-printed models — for example, putting rabbit ears on a frog or swapping out the head atop Michelangelo’s statue of David. This type of personalization is being applied to 3D-printed chocolates and many other gift items offered for sale by enterprising entrepreneurs using nothing more than a handheld 3D scanner, free design software, and a consumer-level 3D printer.

Curated artifacts

Some entrepreneurs use 3D printers to create solid versions of digital models to sell or to exhibit in galleries as showpieces. The Smithsonian Institute’s digital curation team is scanning items from its vast collection, creating 3D models of objects that can be reproduced for display elsewhere without risk to the originals, many of which are simply too fragile or too rare to transport around the world. (See Figure 6-1.) So far, the team has identified 14 million items for eventual capture. The team is using laser scanners to capture high-resolution models from items in the Smithsonian and other locations around the world.

Although the Smithsonian’s digitization project is not a profit-generating effort, other museums and display venues are taking advantage of similar capabilities to create collections of the world’s rarest artifacts without risk of damage or loss; these items can then be licensed for use in other museum displays. Many designs are being captured and shared for free. Figure 6-2 shows some of the artifacts that museums have uploaded to the Thingiverse (www.thingiverse.com) 3D-model repository for public sharing and download. Such models allow people to have examples of the world’s greatest historical artistic and cultural achievements arranged around their living rooms or displayed in a classroom to enrich students’ learning experiences.



FIGURE 6-1:
Digitization of a
bronze statue of
Thomas Jefferson
and its full-scale
reproduction.

Image courtesy of Smithsonian Institute



REMEMBER

As long as the licensing for a 3D model allows commercial reuse, objects created directly on a 3D printer can be sold to schools, museums, or private collectors.

Expanded opportunities

Many jobs are being created to capture 3D models for artifact curation, create cityscapes for urban planners, and capture living organisms for the medical industry. Not all these types of jobs involve simply laser mapping to create the digital model, as Figure 6-3 demonstrates. Unpiloted aerial vehicles (UAVs) are being flown over entire cities to create printable 3D models of buildings through photogrammetry; CT scans are being used to create 3D models of ancient skeletal remains; and ultrasound imaging of fetal development allows a mother to see what her unborn child looks like well before the baby's delivery. New industries are using additive manufacturing, creating the need for new skills and new job opportunities.

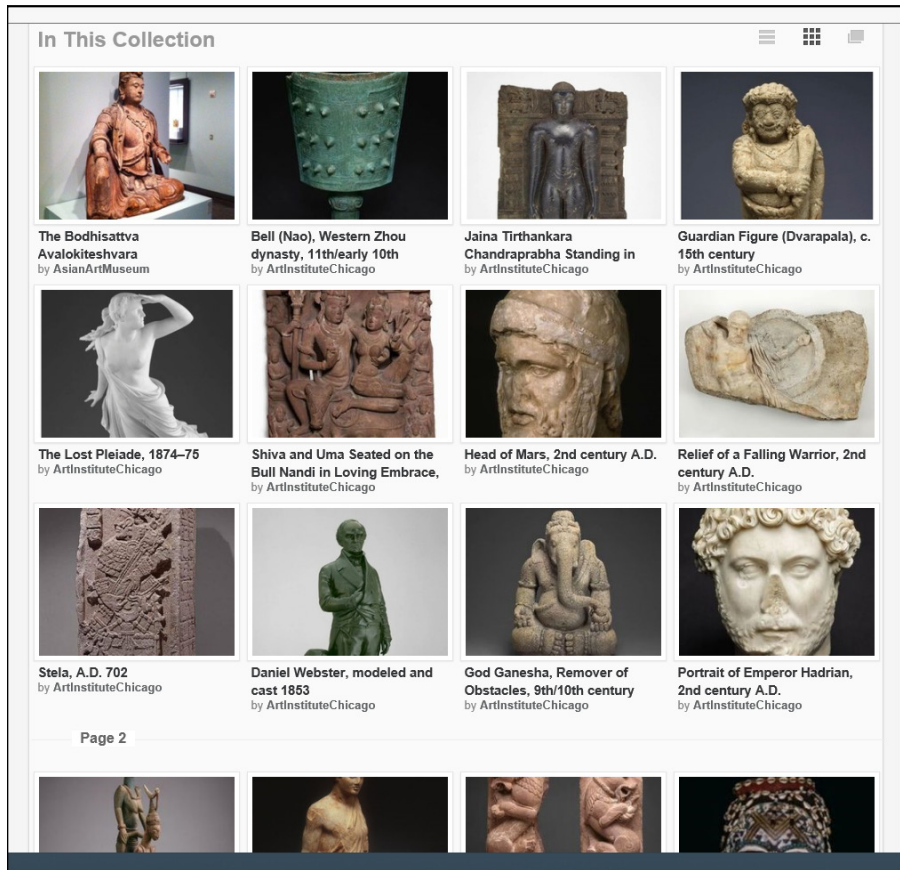


FIGURE 6-2: 3D models of museum artifacts available for download from the Thingiverse repository site.

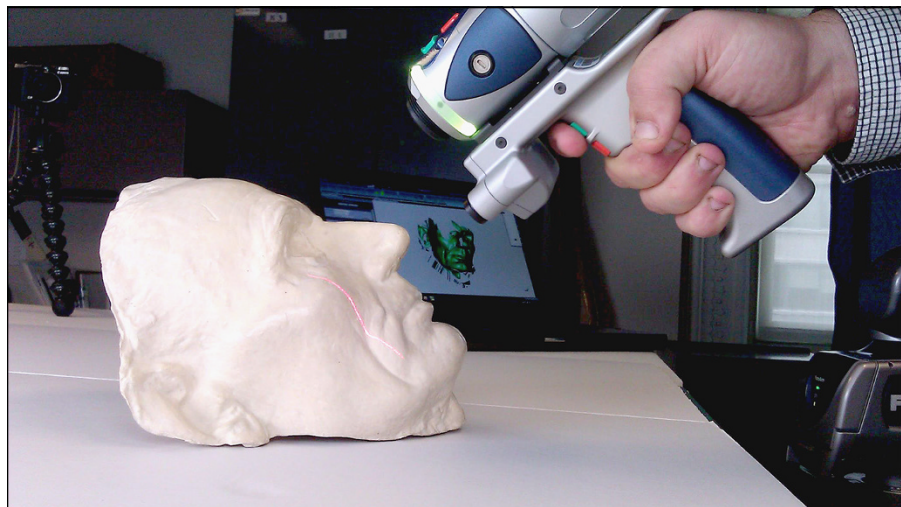


FIGURE 6-3: A FARO laser arm creating a 3D model of this life mask.

Image courtesy of Smithsonian Institute

The studio shown in Figure 6-4 provides an example of a new industry coming out of the 3D model space, where the capture of living subjects sitting still or in motion is providing entirely new techniques for animation and moviemaking. The magnificent car seen in the James Bond movie *Skyfall*, for example, was created using high-resolution scans and a very large-format printer to create a prop in place of an actual 1960 Aston Martin DB 5, which would have been too costly to destroy in an explosion for the movie.

FIGURE 6-4:
3D high-resolution capture studio for facial models.

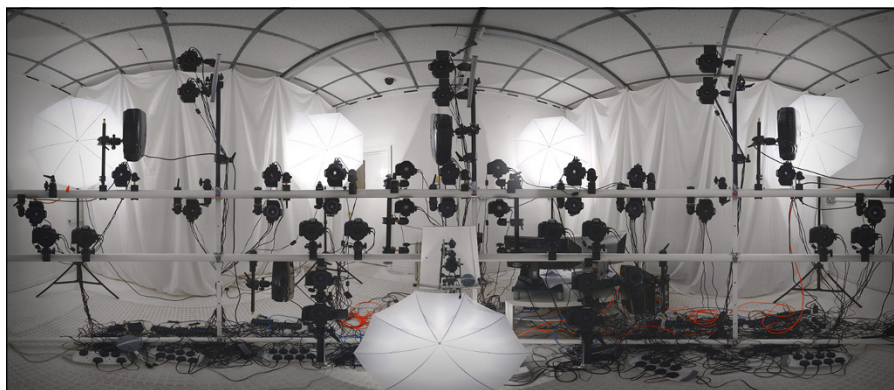


Image courtesy of Infinite Realities/Lee Perry Smith

3D printing has also become fare for story lines in television shows. The hit TV series *Big Bang Theory* features a 3D printer in January 2013. In that episode, Howard Wolowitz and Raj Koothrappali use a 3D printer to make customized action figures. In another TV series, *Elementary*, 3D printing is put in the spotlight again and this time it is used to print a plastic gun. Re-creating specific prop models from television and movies is also generating new opportunities for commoditization, although it simultaneously raises issues of intellectual property rights and control over trademarked or copyrighted designs. An example is engineer Todd Blatt, whose self-created model of the alien cube from the movie *Super 8* resulted in legal takedown notices from Paramount. The studio had already licensed rights to reproduce collectables, including the cube, to another business — creating potential legal conflict resulting from Mr. Blatt's model that could otherwise be simply downloaded and printed at home by fans of the movie. (I discuss the intellectual property implications of 3D printing in greater detail in Chapter 7.)

Selling digital model files instead of physical objects is another option for commodification of 3D printing, providing a valuable product (the design) that can be used to print objects on local 3D printers or at printing services. As additive manufacturing expands into more types of materials and areas of use, boutique design shops can provide 3D-printed overlays and cases for devices, as well as sell 3D model files that can be used to create physical objects.

Establishing personal storefronts

Even if you don't have a 3D printer, you can create an online storefront to sell your designs by taking advantage of services such as Ponoko (<https://www.ponoko.com>), Shapeways (<https://www.shapeways.com>), and i.materialise (<https://i.materialise.com>). These services have their own 3D printers which they allow others to use — for a fee. They allow people to upload their own designs to be printed and shipped in a few days' time. These designs aren't limited to 3D-printed plastic kittens and the like; they can be fashioned with a great deal of artistic style and creative skill. Figure 6-5 shows the online Ponoko storefront of mathematical artist Asher Nahmias, who goes by the name Dizingof.

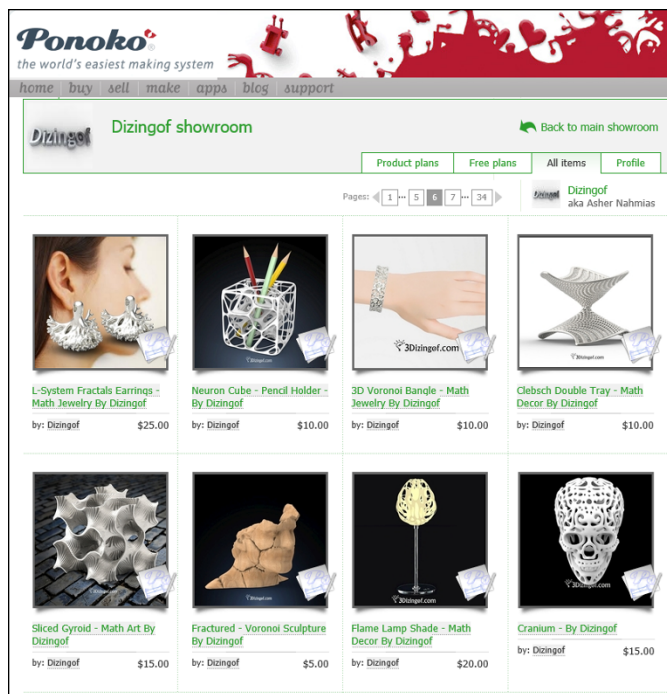


FIGURE 6-5:
The Ponoko
online storefront
for artist Asher
Nahmias
(Dizingof).

Many of the most mature online storefronts for 3D-printed goods are starting to provide their own tools for the design and creation of items to be sold, simplifying things for those hobbyists who don't have strong computer-aided design (CAD) backgrounds.

Creating a unique design

To illustrate the power of services like Shapeways, I created a *For Dummies* 3D-printed keychain fob using one of Shapeways's tools to convert 2D artwork to

a 3D model, as spelled out in the following steps. (Note that every step is free until you order the final object for delivery.)

- 1. Create the black-and-white text and graphic design, using a free online word processor.**
- 2. When you have the text and image the way you want them, save everything as an image on your hard drive.**
- 3. Upload your image to Shapeways's 2D-to-3D design tool, currently at <https://www.shapeways.com/creator/2dto3d>, selecting the thickness of the design.**

You can create the final object here, but to give it a more interesting background and border, you can also add a few optional steps:

- Export the STL file generated by the Shapeways tool, import it into the free TinkerCAD software from Autodesk.*
 - Add a curved, raised border and a solid background to connect the picture and all the letters.*
 - Export the design to your computer as an STL file.*
- 4. Wait patiently for the commercially printed version to arrive.**

The printed item (see Figure 6-6) was delivered in about two weeks.

FIGURE 6-6:
The 3D Printing
For Dummies
keychain fob as it
arrived from the
Shapeways
storefront.



Fabricating a unique product on demand

When you are happy with a model created in the preceding section (“Creating a unique design”), you can upload it to your Shapeways collection so that people can also order it. Object designs can also be uploaded and shared on your own storefront, from which anyone can order it at prices ranging from \$4 (white plastic; see Figure 6-7) to \$85 (polished silver).



REMEMBER

You could use the same process to create your own designs for sale, using nothing more than your own creative drive and free online tools. You can control the type of materials that can be ordered and the prices for each. For this example, all the available material options were selected for an item this small and added \$1 to

the raw production cost as an example of the marketplace functionality. Your own designs can be much more elaborate and priced accordingly; you don't have to create a physical object to get started.

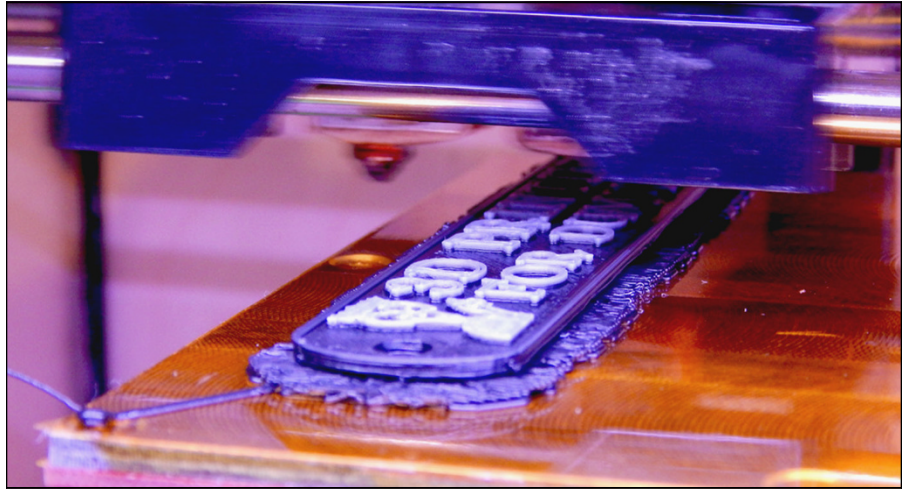


FIGURE 6-7:
The 3D Printing
For Dummies
keychain fob
being created on
a home desktop
3D printer.

The example key fob took about 15 minutes to complete. If you simply want to create custom place cards with your business logo for a table at your next board meeting, you could enter the text and use default options to create each card in a couple of minutes. Currently, it takes a couple of weeks to receive these items from online vendors, but that time is shortening as vendors increase the number of printers they have available for custom fabrication. New materials, such as ceramics and precious metals (such as gold and silver), are being added all the time to enhance the options available.

Services such as Shapeways and Ponoko offer another way to make money using 3D printing — by direct printing of a creator's objects for profit. As with other do-it-yourself sites such as Etsy (www.etsy.com), these vendors profit from their investment in high-end commercial 3D printers that are still well beyond the means of the average citizen.

Because this equipment is available, individual designers can create new boutique industries entirely online — from design to ordering page to fabrication system — until the created object is shipped and delivered to the consumer as a finished product. Design of 3D-printed objects is in its infancy as a new trade, built atop two sets of skills:

- » Technical skills with 3D-modeling software
- » Artistic skills to fabricate designs that aren't possible with mass-manufactured goods

This new model of manufacturing allows the design to be customized for every order; it doesn't rely on warehouses filled with bulk items or intercontinental shipping of goods from a country where labor is less expensive. Additive manufacturing is an early example of the potential for transformative business evolution beyond traditional mass manufacturing.



REMEMBER

Understandably, the potential of this new manufacturing model is creating some concern in countries whose major export is cheap labor for making bulk goods. I discuss the potential for 3D printing to revolutionize manufacturing in greater detail in Chapter 7.

Creating “impossible” objects

Certainly less expensive techniques are available for traditional mass manufacture of a standard plastic product like the keychain fob discussed in the preceding sections. That advantage disappears, however, as the product becomes more complex. Suppose that you want name tags to include a 3D physical representation of each person's facial features next to their names for security purposes and ease of identification. The cost of production would increase dramatically for traditionally manufactured items, if they could be produced at all. At the extreme end of personalization and customization, some structures are simply impossible to fabricate at a reasonable cost. For example, the 3D-scanning studios at Disney's theme parks already employ 3D-printing systems to create custom Disney-princess dolls with a child's face atop Belle's or Cinderella's gown. Disney is also using 3D printing to embed light pipes directly in solid objects, creating custom lighting for its exhibits that uses power-efficient LEDs in place of traditional bulbs or fluorescent coils — illumination with an improved coverage of the area tailored to its specific use and layout.

Another example of the transformative potential of 3D printing involves the reuse of existing objects to produce a design for a new purpose — a traditionally made shoe but with a fully customizable 3D-printed support insole, for example, scanned and produced on-site for a more comfortable fit. Only the customer specific components need to be replaced; costly durable elements can continue to be used until they cease to function.

Building New Tools

Another industry that demonstrates the new potential of 3D printing involves the creation of new tools, both to design objects and to fabricate existing designs. 3D printers need to be able to accommodate the materials and environments in which they work. A 3D printer that uses lunar soil in an airless environment, for

example, requires a few changes from the current practice of mass fabrication of bricks and cinderblock for traditional construction, as would a submersible 3D-printing tool that repairs damaged submarine components during underwater operations or a 3D bioprinter designed to repair living tissues within the human body. The software that drives these new printers also needs to be updated to merge techniques from animation modeling, mathematical structural analysis, and many other disciplines into applications that unleash the amazing potential of these tools.

Moving beyond solid blocks

When we started learning technical drafting in the mid-1980s, traditional tools were used: a pencil and a trusty French curve on a portable drafting bench. (The 3D CAD students of today should be aware how time-consuming this was when they complain about how hard it is to learn solid-modeling techniques.) CAD software has evolved to two-finger manipulation on a tablet, yet the final results are attractive enough to hang on the wall. Some cleanup is required to address overhangs and inner geometries that would result in loose components rattling around in an internal void, but most CAD software is designed to create solid objects.

Certainly, the objects may have hollow channels and cavities; they can even include multiple components consolidated into the final shape. Most CAD programs, however, still design objects with a definite volume and definite boundary areas, resulting in relatively solid materials in the final form. 3D-printed objects are being designed with different material types and structural densities throughout the object, created in a single pass, without assembly of subcomponents in the final stages of manufacturing. Objects are printed already combined!

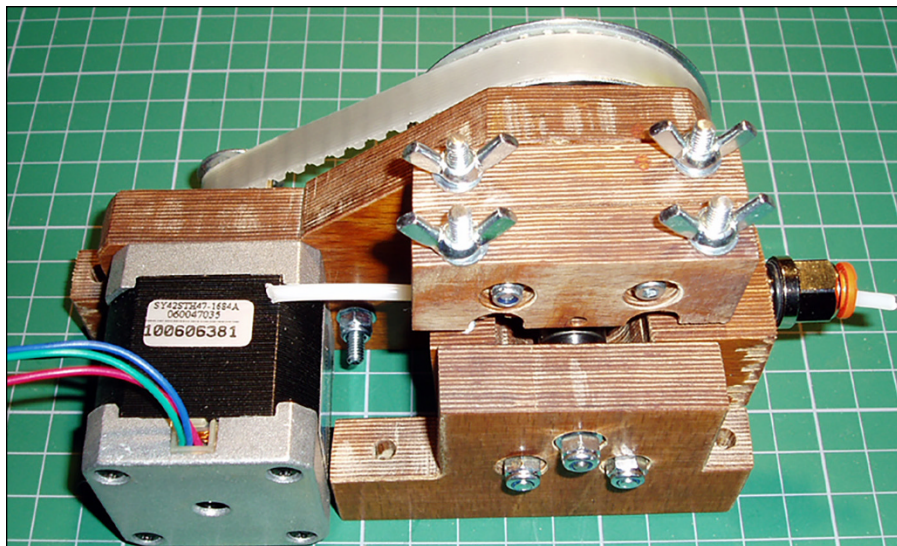
These tools are creating new industries as their capabilities are realized and new applications are found in a production environment. The products that emerge are more akin to organic designs than solid-block objects. 3D-printed fabrication offers new production capabilities and resource efficiencies that will affect multiple industries. No wonder so many new opportunities for software designers are beginning to flourish in this space.

Creating the tool that will create the tool

Making tools to make other tools is a time-honored activity. When the first examples of RepRap 3D printers emerged in 2005, the entire machine was often handmade from old or discarded CNC parts and even the guts of old 2D printers for the moving mechanisms and motors. The extruder module was often handmade from wood or plastic sheets and off-the-shelf gears or belts. My very first *RepStrap* (that's a bootstrapped RepRap) extruder was handmade from wood and off-the-shelf gears. (See Figure 6-8.) It didn't take long for an improved 3D-printed design to be made with these first wooden extruders. These new

printed models replaced the originals and improved the print quality, so the cycle continued until an extruder — and then almost all of the other printer parts needed — could be 3D-printed by anyone around the world.

FIGURE 6-8:
My handmade wooden extruder that allowed my first RepStrap to print out the parts needed to make a Prusa i1 RepRap based on the Mendel design from the University of Bath (UK).



After an initial bootstrapped machine was up and running, it was less likely you'd need to pick up the hand tools to ever make another wooden part. From that point on, the parts could all be 3D-printed. This same process of printed iteration and design improvements then happened hundreds of times to refine desktop 3D printers into the machines we have today. Back in the early days of 3D printing, my reply to people asking “What do you actually make with a 3D printer?” was “At the moment, I make more and better 3D printers.” This was the community and the hobby that started it all. Tools making better tools without actually needing to pick up a traditional tool drove people on to design better variants of 3D printers. The best survived and lessons learned for the ones that didn't make the grade.



TECHNICAL
STUFF

If you want to see the entire journey of my first handmade 3D printer way back in 2011, it's all available on my blog at <https://richrap.blogspot.com/2011/01/goals-for-repstrap-v20-machine.html>. For me, this machine started the capability to self-replicate parts to build more and improved RepRap 3D printers; I'm still on that wonderful journey well over a decade later.



REMEMBER

After you have a 3D printer it's quite possible to print out a set of parts to build another 3D printer; that's the fundamental aspect of the RepRap project and what started the entire desktop 3D revolution. When all you need is a 3D CAD package, some plastic filament and a basic 3D printer, you can make a much more capable machine by improving the parts. (See Figure 6-9.)

The set of 3D-printed parts shown in Figure 6-10 were used to build an early desktop 3D printer from 2011. (See Figure 6-10.) This design is the great, great grandfather of the now incredibly popular Prusa i3 generation of 3D printers, with the MK4 model being launched in 2023.

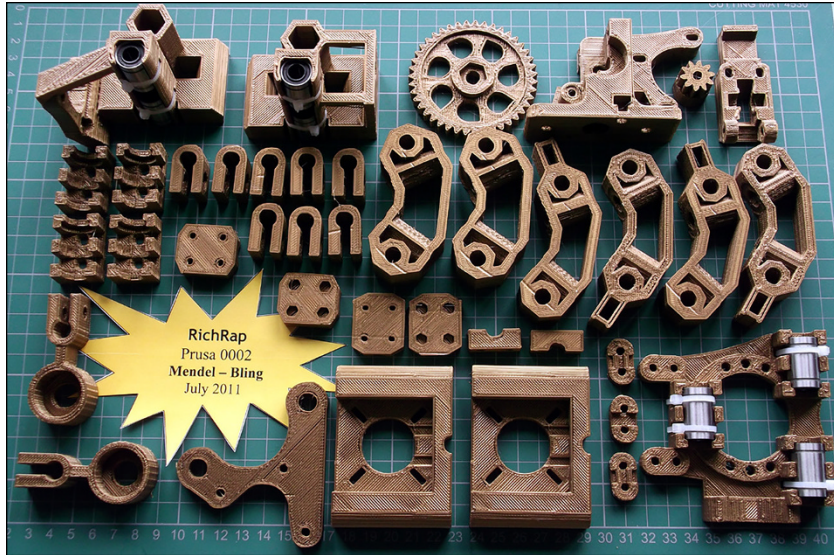


FIGURE 6-9: My first full set of printed parts to build a Prusa i1 machine from 2011.

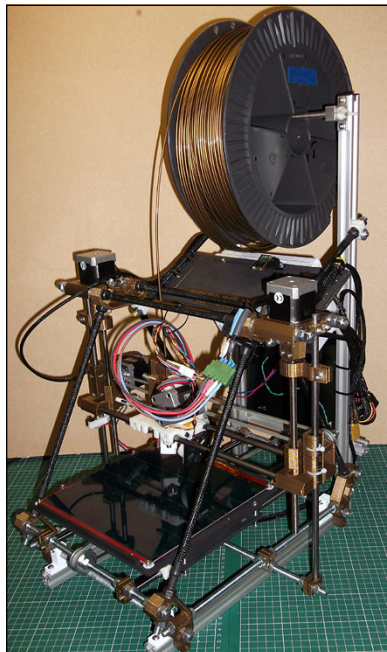


FIGURE 6-10: The Prusa i1 from 2011 started an iterative design generation of 3D printers that is still evolving today.

IN THIS CHAPTER

- » Understanding changes to production
- » Handling challenges to intellectual property laws
- » Using expired designs
- » Being ethical

Chapter **7**

Understanding 3D Printing's Effect on Traditional Lines of Business

As I discuss in Chapter 1, the transformative potential of additive manufacturing is so great that we are already in the middle of a third Industrial Revolution (See Industry 4.0), one in which local production is displacing less flexible and resource-intensive traditional manufacturing processes. This chapter discusses the potential disruptions resulting from this ongoing evolution and its likely impact on not only traditional manufacturing, but also personal individualized manufacturing.

Transforming Production

In addition to using sustainable alternative materials such as polylactic acid (PLA) instead of traditional petrochemical-based materials, additive manufacturing could bring back home manufacturing tasks currently outsourced to locations that offer lower-cost mass production. Such a shift, in turn, may affect the industries involved in the transportation and storage of mass product quantities and reduce the environmental impact of cargo transportation. Manufacturing in less industrialized settings may also result in less environmental impact and lessen the need for regulation.

Many strategies for recycling become possible where a part is generated on the fly, used, and then recycled instead of just discarded. 3D printing may one day allow manufacturers to transform everything from solid objects and construction materials into new appliances or buildings without any waste.

The fundamental technologies behind additive manufacturing may also transform the materials (and quantities thereof) used in the production of goods, which could affect industries that currently supply parts to existing production lines. As manufacturers become more capable of low-impact (green) production of lighter weight structural frameworks (with complex interior designs like a bird's wing bones instead of a solid mass of steel or aluminum, for example), major changes in the production process may be triggered along the following lines:

- » Reduced quantity of material needed for the same result
- » Improved potential for reuse of recycled source materials
- » Stronger, lighter products created closer to their markets

The resulting energy savings would be passed along to industries that currently consume fuel and energy in the traditional manufacture of goods. One result would be an environmentally friendly effect on second-order consumption in terms of a reduction in input resource requirements due to the changes made possible by — rather than as a direct result of — using 3D-printed products.

Displacing the production line

The potential presented in additive manufacturing as it matures suggests a fundamental transformation in the production of material goods. Supporters like to discuss the possibilities of ad hoc personalized manufacturing at the consumer level, whereas critics argue about the damage any transition from traditional mass-manufacturing, storage, and distribution would make on existing economies.

These concerns are the same that buggy-whip makers and farriers had when machines replaced horse-drawn carts, when hand-spinners were replaced by automated thread makers, when coopers faced the rapid production capacity of injection-molded barrels, and when automated looms transformed textile production capabilities. All these examples occurred during transformational stages in the first and second Industrial Revolutions.

With the potential already developing to print everything from engine parts to whole houses by moving production directly to the consumers' sites, many cargo container ships will be put out of business if the 3D Industrial Revolution reaches a fraction of the promise of its potential.



REMEMBER

3D printing, crowdfunding, robotics, ad hoc media content, and a host of other technologies — taken together — will not only alter the course of production but fundamentally shatter traditional manufacturing practices and related industries such as advertising and marketing.

In engineering settings, the success of additive manufacturing has been thoroughly proven. Consider the reconstruction of the Saturn V's colossal rocket motors by NASA scientists. This technology was designed to provide heavy-lift capability for the Orion system that will replace the retired space shuttle for manned exploration of the moon and Mars. 3D printing is preparing the vehicles that will carry future astronauts. 3D printing will provide them with the tools and possibly even the food they'll need during their journeys.

In medicine, 3D printing may soon provide replacement parts for human bodies. The military is also finding many uses for 3D-printed-in-the-field rapid prototypes.

Abbreviating the manufacturing chain

Traditional manufacturing involves a sequence of events that take place in scattered locations. Manufacturing a cellphone's lithium battery, for example, involves these steps:

1. Collect basic resources such as iron and lithium.
2. Transport the materials to locations where materials for individual components, such as steel and intercalated lithium compound, can be refined.
3. Transport the refined materials to sites for processing and finishing into subassemblies such as batteries.
4. Transport the subassemblies to locations that assemble the finished product.
5. Transport the finished product for consumer packaging.
6. Transport the packaged product to customers.

Thus, when you shop for the newest cellphone at a store near your home, you're at the far end of a long chain of events. The manufacturing cycle looks different for an equivalent product of additive manufacturing:

1. Collect basic resources.
2. Create needed materials from collected resources.
3. Transport materials to a fabrication site in each town or region.
4. Have individual customers select product options before manufacturing.
5. Use data files that define the product design to fabricate a specific model of the final product that includes the chosen options.

In addition, recycling earlier products as feed stock for the production of complex, multimaterial designs would reduce costs to consumers and encourage the recovery of materials that would otherwise end up in ever-expanding landfills.

Providing local fabrication

Some goods, such as coat hooks and children's party favors, can already be produced easily on a consumer-grade 3D printer. A search of Etsy or almost any other online shop providing products for common hobbies and pastimes shows many other products that can be made at home today, including miniature figures, drones and model aircraft, board games, plastic eyeglasses, jewelry boxes, and cellphone cases. Also, making these items at home means you can customize them.

UPS deliveries, Amazon, and other online marketplaces are researching how items can be fabricated locally and delivered to consumers via drones without traditional manufacturing and distribution chains. Soon, mobile fabrication centers may travel ahead of events such as concerts to prepare personalized items for sale or traveling in the wake of storms to provide items that are useful in recovery.

Researchers are exploring ways to use natural materials to fabricate protective structures for just such a need. Markus Kayser at the Massachusetts Institute of Technology built his original Solar Sinter to use the abundant sunlight and natural sand available in Egypt to fashion durable items and prototype structures. NASA and the ESA (European Space Agency) are exploring automated systems that will build shelters on the moon. Those same technologies can be applied on Earth with equal ease because the models cost almost nothing to duplicate from one computer to the next.

Eliminating traditional release cycles

Globally, the transition between seasons imposes a cycle of goods suitable for warm and cool weather. Similarly, massive corporate marketing efforts update durable goods for the next cycle's models to attract consumers and ensure continued sales to sustain manufacturing growth. Some cycles provide actual improvements and innovations; others make purely cosmetic changes. As cycles of change are repeated, repair parts become scarce, and costs to service the original design rise. Automobiles have exhibited this trend over many years. Components for a vintage collectable such as a World War II-era Willys Jeep, for example, are increasingly unavailable except from specialty providers that charge high prices in keeping with item scarcity.

Handling Challenges to Intellectual Property Laws

The United States, the European Union, and other members of the World Intellectual Property Organization (WIPO) provide legal protections under patents for both *utility* (functionality) and *design* (ornamental design of a functional item). During the term of a patent, owners can prevent the unlicensed use of their registered intellectual property (IP) designs in products for sale, and licensees must pay a licensing fee.

Threatening IP protections

Design patents provide protection against the duplication of a particular object's physical form but are intended to encourage competition through the development of derivative designs that can be patented by their creators. The grant of a patent requires that the work be original and nonobvious.

Physical designs such as the alien cube from the movie *Super 8* and nonfunctional movie props (such as the Oscillation Overthruster prop from the movie *Buckaroo Banzai*, which was later used in several episodes of *Star Trek: The Next Generation*) may be protected under copyright, which protects nonfunctional designs from being copied for sale. The difficulty for IP owners is that designs can be copied from photographs, which can be taken from a distance without the owner being aware of the duplication.

This situation presents a challenge for manufacturers. The body design for a new car, for example, could be captured by a photographer, transmitted to a fabrication facility, and made available as a 3D-printed overlay for last year's model before the new version is in the manufacturer's showrooms for sale.

Because additive manufacturing allows people to copy or create new items similar to patented designs, existing patent laws will need to be updated. Until the laws change, however, the technology will continue to cause trouble.



The plastic tank model shown in Figure 7-1, for example, is Thomas Valenty's design for a model used in playing the Warhammer board game, created by Games Workshop. This model isn't a direct copy but has a similar look and feel. Valenty's posting of his model online resulted in a challenge by Games Workshop, which claimed that the 3D design violated its IP rights. That is, if someone downloaded Valenty's design, they wouldn't need to buy the official object from Games Workshop. The Thingiverse repository received a takedown notice on the basis of protections under the Digital Millennium Copyright Act (DMCA), which is better known for suits against illegal sharing of music and video files. This notice was intended to prohibit people from downloading a copy of the design that could be used to create an object for personal use.



FIGURE 7-1:
A 3D-printed copy
of Thomas
Valenty's tank
model for
Warhammer.

Assigning legal liability

At this writing, people can make items for their own use without having to retain a lawyer and pay for a full search of all IP registrations to identify potential conflicts. This is true of patented designs. You can write your own operating system, which can look like a commercial design, as long as you don't distribute it to

others. You can duplicate the trademarked shape of protected soda bottles for personal use at home. Now that a person without significant design skills can create a replacement part for an older car that may be protected intellectual property, there's potential IP trouble. The legal system is trying to come to terms with how to protect designers' right to make a profit from their designs and people's right to make their personal items without an impossible level of cost and legal review.



WARNING

If a component or other product fails to function properly, often, the result is recalls and replacements in the world of traditional manufacturing. Consumers who create copies of such items may unwittingly take on liability for any damage or harm resulting from the use of that component or product. If you use a 3D-printed vacuum cleaner produced at a local fabrication site of the sort that UPS envisions (refer to “Providing local fabrication” earlier in this chapter), and the handle fails and causes injury, where does the legal liability lie? Is the defect the original designer's fault? Is it the fault of the manufacturer or individual, which may have used different materials? Is it the fault of the owner who paid for the replacement part, who may not even have known that the part wasn't an official factory-manufactured replacement? Traditional insurance and legal rules that determine liability need to be updated in the years ahead to reflect 3D-printing innovations.

Leveraging Expired Patents

Patents protect designs, but what happens when they run out? Items that age out of the system are no longer protected by IP restrictions. Any object older than the term of patent — or released from patent due to discovery of earlier art or failure to pay the applicable fees — can be produced by any manufacturer for sale. Many expired designs are being converted to be 3D model files that can be downloaded from Thingiverse or ordered from the storefront at Shapeways (www.shapeways.com).

Currently, the U.S. Patent Office has illustrated diagrams of more than 8 million patents granted since the Patent Act of 1790 allowed citizens to apply for a patent. The vast majority of these patents have expired and are available for reproduction. If the current laws are retained, nothing will stop entrepreneurs from bringing back many collectibles and offering 3D-printed reproductions for sale. If the files that define 3D models of designs become protected under *copyright* law instead of patent law, however, use of these designs could be delayed for centuries. Copyright protection lasts until 70 years after the author's death; advanced geriatric care and new medical procedures could extend human life well past the century mark before the 70-year countdown even begins.

Rare items are rare only because they're no longer being manufactured. Obviously, collectors of rare items depend on their investments to be protected and want to prohibit unlicensed manufacture. A 1971 factory-original Plymouth Hemi Barracuda, for example, was recently offered for sale for \$2 million USD. If a 3D-printed '71 Barracuda became available, collectors would surely try to print one. Owners of the few remaining original cars, however, would feel that their investments were threatened.

Working around patents

Additive manufacturing is still in its infancy, and many of the designs for rapid fabricators are still under patent protection. The expiration of patents on two early modeling techniques — stereo lithography (SLA) and fused filament fabrication (FFF) — opened the way for the development of the many open-source RepRap variations, as well as the new boutique production of home printers like the Form 1. Critical key technology patents covering laser-sintered granular-bond fabrication expired in 2014. These expiring patents create potential for many new commercial and hobbyist systems. Eventually, this situation will not only bring down the cost of creating 3D-printed objects from metal and other materials but will also offer new opportunities for creating and commoditizing such objects.

Not all IP controls have been holding back the floodgates, however; some patent protections encourage development in 3D printing. When 3D Systems held all production rights for stereolithographic fabrication, another company sought alternative ways to use photopolymerization without relying on a liquid pool for fabrication of the developing object. Objet (now combined with Stratasys) developed the photopolymer PolyJet technology from inkjet printing methods, allowing the application of thin films of liquid plastic that could be rapidly hardened by ultraviolet light.

This photopolymer process is much easier to manage without the large vats of liquid plastic needed for SLA fabrication, but each technique provides its own advantages. Some of the largest and most precise 3D printers use variations on stereolithographic and multiphoton lithographic fabrication. (For more on that topic, see Chapter 2.)

The process is similar to the way 2D printers mix colored inks to create full-color photo reproductions. As a result, Objet's printers can create objects whose physical properties vary from one point to another — even throughout the object itself! — to allow flexibility in one area, a higher frictional surface in another, or variations in transparency and color for aesthetic or functional purposes.

Without the barrier created by 3D Systems's control of the original SLA patents, the PolyJet alternative might not have become available. As the earliest additive manufacturing technologies come out of patent control and new technologies are developed, opportunities will emerge for the transformation of manufacturing and the production of new products.

Protecting intellectual property rights

New technologies create a threat to the intellectual property of established companies. As long as self-built 3D printers are available, however, mandatory digital rights management (DRM) controls are likely to remain absent in home-production systems. Commercial vendors may be forced to comply with some type of DRM solution, with complex algorithms scanning each model to see whether it violates someone else's intellectual property or includes items restricted from fabrication.

It will be necessary to develop a database of all protected IP designs and then create a search engine that can be linked to a 3D printer's software to approve or deny the fabrication of a particular design. Aside from potential attacks on such a service from people who support open-source design, not much will prevent an operator from bypassing a designer's controls on the type of materials that can be used, replacing (say) an aluminum powder cartridge with a gold powder cartridge, regardless of whether the designer ever intended a solid gold version of the object.

Imposing Ethical Controls

Some objects are protected from duplication by virtue of their use, such as firearms and high-security keys for locks. New systems promise to inhibit the creation of 3D-printable firearms by identifying characteristic components, which could run into problems when they block the fabrication of any tube that is 9mm, 10mm, or any other diameter matching firearm ammunition. Just as with DRM, as long as self-created 3D printers are available, any software controls can be bypassed to allow the fabrication of protected designs.

Figure 7-2 shows the Liberator, the first 3D-printed functional firearm. (Note that we modified the firearm from its original design files in various ways to render it inoperative.) These weapons present difficulties for law enforcement because, although the designs are intended to comply with current U.S. laws for legal firearms, they could be modified to be undetectable by current security scanners.

FIGURE 7-2:
The 3D-printed
Liberator firearm,
modified to be
nonfunctioning.



It's equally possible to fabricate (scan and 3D-print) controlled designs such as high-security keys for handcuffs and other secure locks. Because these functional keys are made of plastic, they could be carried through metal detectors by criminals. Students at MIT recently created 3D-printable models of the controlled key blanks used by Schlage's Primus high-security locks. The uncut key blanks normally can't be acquired by civilians. Researchers have been able to duplicate keys from photographs captured from up to 200 feet away, needing only the blanks to create fully functional keys capable of bypassing traditional physical security controls in government, medical, and detention facilities.

As 3D-printable drugs, body tissues, and organs become available, ethical control of this new form of manufacturing will be difficult. Where we once were concerned with athletes doping their blood, we may someday have to find ways to identify custom body modifications that allow all manner of extreme physical feats.

Software alone will not provide a technical solution to control the ethical or unethical uses of products that were once simply impossible but which are now becoming more than possible. Medical researchers may present more than just 3D-printed tissues for reconstructive surgery and medical treatments in a few decades. Legal controls such as patents are already facing challenges when applied to biological organisms; digitally fabricated viruses and other materials are entirely possible and will present a spectrum of difficulties in their application, liability, and legal controls.

- » Exploring emerging areas
- » Designing functional technology
- » Experimenting with new materials
- » Employing 3D printing in space
- » Working with 3D printing in health care

Chapter 8

Reviewing 3D-Printing Research

Additive manufacturing applications already suggest fundamentally transformative potential across many areas of manufacturing and production. The technology's true potential, however, is still being discovered. Research continues on applications that can translate virtual digital models into physical forms in a variety of fields. This chapter reviews current research on the next generation of additive manufacturing techniques, materials, and technologies.

Building Fundamental Technologies

New discoveries take time to develop into their mature forms. The discovery that magnetism can be created at will by passing an electrical field through a loop of wire introduced new possibilities in electricity and electronics, and these developments, in turn, led to technologies such as computers and cellphones. The emergence of automation transformed manufacturing; now the combination of computers, robotics, and many other disciplines allows us to fabricate small plastic objects at home as easily as we print recipes on our home inkjet and laser

printers. As researchers continue to expand the capabilities of 3D printers, they create new tools that can lead to capabilities we can't even imagine now. Here, however, are some technologies that we *can* imagine.

Crafting educational tools

Any new tool provides only limited value until its operator has been trained in its proper use, so opportunities are emerging for teachers who will educate future operators of additive manufacturing systems. Many schools are starting to develop programs on 3D printing and its remarkable potential. These programs test new innovations and their applications — from 3D-printed foods at Cornell to printed plastic boats at the University of Washington. Obtaining a personal 3D printer is inexpensive and easy when the tool can make the tool: A single 3D printer in a school can be used to create more 3D printers so that they become more available to educators and students.

To develop the next generation of scientists and engineers, the Defense Advanced Research Projects Agency (DARPA)-sponsored MENTOR program started placing commercial-grade 3D printers in select high schools around the United States, the United Kingdom, Australia, and South Africa. The program develops strategies that allow teachers to incorporate 3D-printed materials and tools into their existing curricula to enhance student learning. See Figure 8-1 for an example of a 3D-printed centrifuge used in schools.

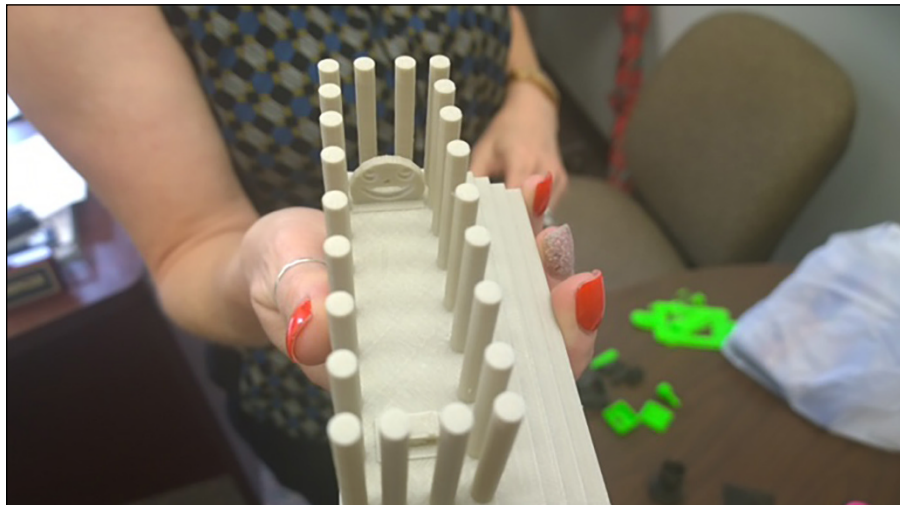


FIGURE 8-1:
Example of a
3D-printed design
for centrifuges
used in schools.

The advantages of having 3D printers in school don't stop there. Teachers often have difficulty maintaining sufficient equipment in a given class, especially as student population shifts from one year to the next. By using 3D printers, however, teachers can create lab equipment and classroom examples for several courses, from solar-powered water-electrolysis systems to 3D-printed models of artwork or animal bones. Figure 8-2 shows some high schoolers at Texas A&M University creating designs for 3D printing.



FIGURE 8-2: High schoolers in Texas A&M University's summer program create designs for 3D printers.

Kalani Hausman / Flickr / CC BY-SA 2.0

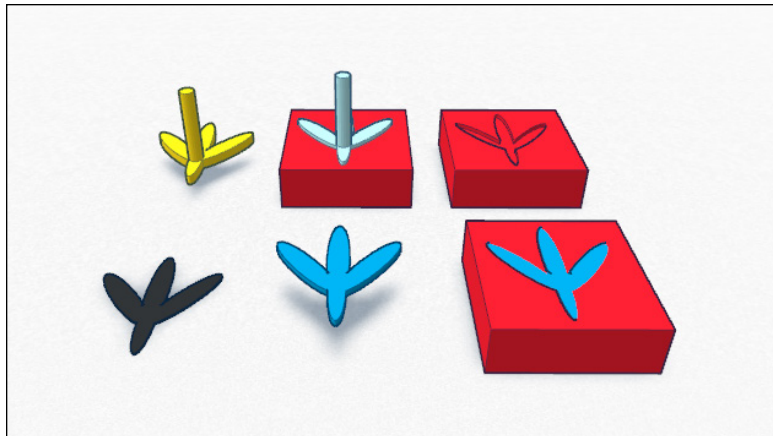
In addition to no-kill “dissectible” animal models and replicas of ancient cultural artifacts for students, teachers can create mathematical and aerospace designs for testing in the lab, using tools such as a wind tunnel that was itself 3D-printed into existence. 3D molds of animal footprints that teachers can fill with common liquid rubber and silicone compounds to create stamps are another example of 3D printing assisting the learning process. (See Figure 8-3.)



REMEMBER

By building RepRap printers that use stepper motors from surplus 2D printers and other basic items from local suppliers, students learn basic mechanical and electrical controls, robotic feedback systems, and computer drafting and 3D modeling. They also learn the properties of various materials and the advantages of sustainable development.

FIGURE 8-3:
3D-printed
animal foot
molds, starting
with a scanned
animal's foot and
concluding with a
footprint stamp.



Expanding 3D-printing options

Since the 3D printers that solidified objects in a vat of liquid photopolymer first became available, the quality of resolution and detail in 3D-printed products has improved hundreds of times. Even liquid photopolymer printers have improved: Researchers at HRL Laboratories are developing innovations such as the micro-lattice lithographic system to provide new capabilities for photopolymers.

As I discuss in Chapter 7, intellectual-property restrictions on the basic stereolithographic (SLA) patent motivated the manufacturer Objet to develop the PolyJet. Expect this process to continue; other companies are driving ahead with new systems capable of achieving lower-cost operation, greater speed, and greater build volume, as well as working with a wider range of materials. Researchers are continually developing strategies for depositing materials one layer at a time to transform a virtual model into physical form. Even the basic self-replicating rapid prototyping (RepRap) system designed by Dr. Adrian Bowyer, for many years a senior lecturer in the Mechanical Engineering Department at the University of Bath in the UK, has seen many iterations derived from the original Cartesian system that drove motors in X-, Y-, and Z-axis movements. Today's Delta and polar systems reduce the overall complexity (and cost) of 3D printers. Quentin Harley, a South African designer, has been evolving his polar-style Morgan RepRap (shown in Figure 8-4), reducing the cost of his creation to well under \$100.



REMEMBER

As each researcher and designer examines and updates the basic technology of 3D printers, and as original patents expire, a tremendous expansion in capability occurs. Preliminary patents on SLA and fused deposition modeling (FDM) fabrication have expired. As a result, many new opportunities in consumer-level 3D printers have arisen, and researchers are spending considerable time preparing for these opportunities.

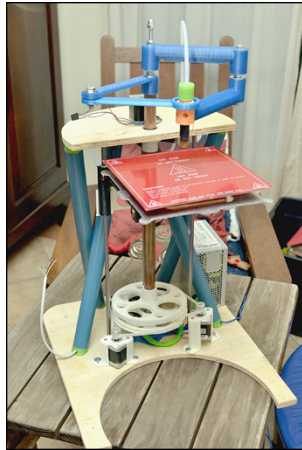


FIGURE 8-4:
The low-cost
Morgan RepRap.

Image courtesy of Quentin Harley

Fabricating 3D-printed electronics

Fully 3D-printed electronics are of significant interest in both commercial and hobbyist applications. Researchers at the University of Warwick have created conductive polycaprolactone (PCL)-based filament by mixing carbon black into melted plastic before it's extruded as filament; they call the result *carbomorph*. Carbomorph can be used to print circuits directly into objects, eliminating the need for wires and conduits in traditionally manufactured electronic devices. Carbomorph's physical properties also allow it to be integrated into other objects and 3D-printable materials, creating sensors directly within the object itself.

Creating Functional Designs

The Walt Disney Co. is examining ways to integrate electronics into 3D-printed objects to create the next generation of toys, like the chess pieces shown in Figure 8-5, which can display a current board position or one planned by a computer adversary.

Many of today's 3D-printed electronic devices focus on basic sensors and more complex light guides for displays and integrated circuit paths. Research continues to explore increasingly complex fabrication techniques that could soon print a whole device, including its electronics, from a single design file. Imagine 3D-printed batteries and photovoltaic panels providing power to 3D-printed circuitry and displays, controlled by 3D-printed sensors — all in the same solid form. Today, 3D printers are producing working models of objects that are well beyond the capabilities of the original nonfunctional rapid prototypes that additive manufacturing was developed to produce.

FIGURE 8-5:
Examples of
Disney's
integrated
electronics in
interactive chess
pieces.

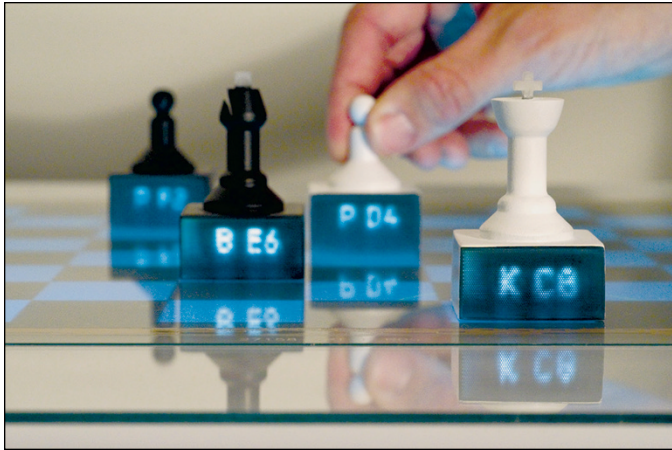


Image courtesy of Karl Willis/Disney

Drones, robots, and military applications

The U.S. military is trying to develop 3D printers that can create drones and robots, printing not only structural elements and control electronics, but also microbatteries and control surfaces. When this capability is achieved, a single fabricator can be dropped in a forward area and used to fabricate multiple drones, unmanned submersibles, or terrestrial robots to gather intelligence and protect fighters in hostile areas.

If this capability is expanded to include explosives, the same fabricator could churn out a stream of agents that could prosecute a war remotely — or independently — guided by technicians who have completed programming before the explosives are deployed without risk to the originating country's citizens. If this capability is coupled with advances in artificial intelligence, some researchers are concerned that a *Skynet*-like threat straight out of the *Terminator* movies could emerge as a result of an enemy-hacker compromising the control systems.

Direct production of functional devices is being studied at the University of Southampton, which is developing a Low Orbit Helium Assisted Navigator (LOHAN) high-altitude space-plane prototype. The university previously developed the 3D-printed Southampton University Laser-Sintered Aircraft (Sulsa), the first fully 3D-printed scale-model aircraft. Airbus and other commercial airline companies are exploring the potential to fabricate entire full-scale aircraft, using a massive 3D printer. The goal is to minimize weight and use less material while providing the same structural strength as existing material and reduce the amount of postproduction assembly required.

Von Neumann machines

Self-replicating nonorganic life forms were described by mathematician John von Neumann in the 1940s, but the first mention in literature of machines building machines extends back to the early 1800s. Von Neumann's ideas have found their way into many artistic creations, including the television series *Stargate*, in which Replicators formed from basic building blocks (see Figure 8-6) harvest local resources to create more copies of themselves.



FIGURE 8-6:
A 3D-printed
prop Replicator
block.

Although these creations are fictional (no self-replicating robots exist today), a RepRap 3D printer can print many of the parts needed to fabricate a second 3D printer. That capability is an early step toward self-replication. If future self-replicating robots could gather their own materials from the environment, a nanotechnology-manufacturing weapon might inadvertently convert all natural resources to a gray goo composed of nothing more than nanofactories trying to create more nanofactories. Researchers are trying to create automated fabrication factories to gather raw materials from seawater or lunar soil while protecting against even the possibility of runaway expansion and a theoretical gray-goo end-of-the-world scenario.



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Potential uses for nanoassemblies and nanotechnology are discussed in greater detail in *Nanotechnology For Dummies*, 2nd Edition, by Earl Boysen, Nancy C. Muir, and Desiree Dudley (John Wiley & Sons, Inc.).

Expanding Material Selection

Many materials are covered in Chapter 4, but the number of materials is in constant flux as researchers create new or hybrid materials to provide additional capabilities through 3D printing. The conductive carbomorph is an example of a hybrid composite material made from melted thermoplastic mixed with carbon black to create a composite material that can be extruded with standard acrylonitrile butadiene styrene (ABS) settings on a standard 3D printer and yet can also conduct electricity.

Other options include different colors of filaments, filaments with metallic glitter, thermal color-changing plastic, and glow-in-the-dark pigments and dyes. Composite filaments with carbon fiber strands can change and often improve the final properties of basic materials such as nylon and PETG. German researcher Kai Parthy and others are adding materials that are compatible with consumer-level printers. One example that uses such composite materials is LayWood3, a material that looks like wood and can be machined like wood for finishing. (See Figure 8-7.) Other consumer-level examples include LayBrick (a material that resembles sandstone, intended for architectural modeling) and BendLay (a translucent and flexible filament for light pipes).



FIGURE 8-7:
A 3D-printed
“wood” and
Bamboo printer
built by your
esteemed author.

A recent development in 3D-printing materials involves 4D printing. No, the process doesn't create a theoretical multidimensional object like the tesseract (shown in standard 3D in Figure 8-8). In 4D printing — according to its developers at MIT — materials are arranged during fabrication so that a reactive material is placed alongside a flexible material to create a fused sandwich of the two. When fabrication is complete, warming the reactive material causes the printed object to deform or change its shape, much as adding water to a compressed soda-straw wrapper makes the wrapper expand away from the droplet. In other words, the object is printed in three physical dimensions but is expressed fully only across a period of time (time, according to Albert Einstein, being the fourth dimension).

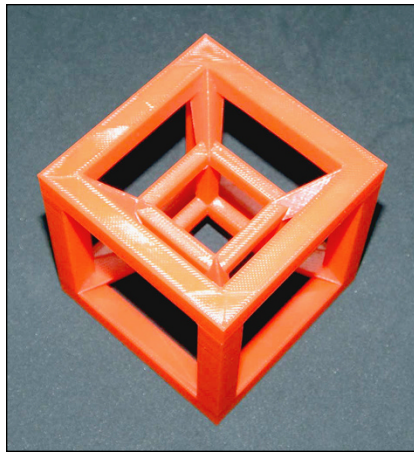


FIGURE 8-8:
A 3D model of a
theoretical 4D
cube called a
tesseract.

Supporting Long Space Voyages

The U.S. National Aeronautics and Space Administration (NASA) is researching technologies that will support manned exploration beyond the Earth's atmosphere, including a special FDM 3D printer being sent to the International Space Station. Further space applications include

- » Printers that use electron beams to melt wire instead of blown metal granules for use in near-vacuum environments
- » 3D-printed nozzles and other components of spacecraft engines
- » 3D printers capable of fabricating living areas for explorers by using nothing more than local materials and sunlight for power (see Figure 8-9)

- » Long-duration foodstuffs that can be printed in solid form from powders and water
- » Bioprinters capable of producing everything from edible meat for astronauts' protein needs to body tissues and organs for advanced medical care during extended voyages

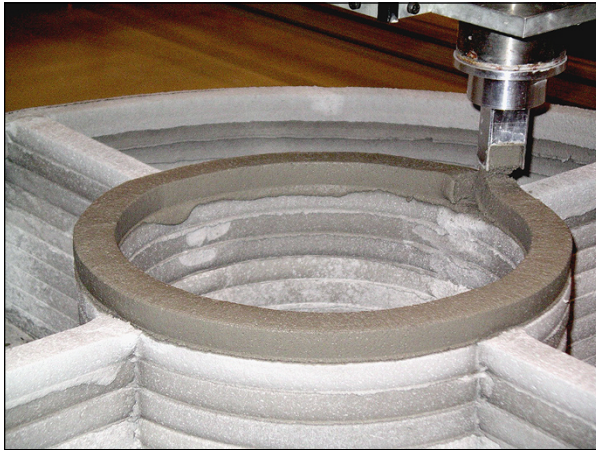


FIGURE 8-9:
A prototype of a
multichambered
lunar habitation
module.

Image courtesy of Contour Crafting

Repairs may involve a space vessel or even a shelter far from home. NASA is investing in research to provide astronauts all the tools they'll need during their trip, even if a particular tool hasn't been invented by the time they leave Earth. If this technology is developed, astronauts won't have to take along a copy of every possible tool to have a spare; they can take only spare items for the 3D printer, many of which could be printed on another 3D printer. Also, this technique would make multipartner international exploration easier, eliminating the need for a metric wrench when an English wrench is needed (or vice versa) to fix a component fabricated in another country.

NASA hopes to eventually mine asteroids and other orbital bodies for materials for space vessels, space stations, and solar power plants built entirely in space. On a large-enough scale, this capability could provide power to ground stations from orbit and even cast shadows to reduce Earth's temperature. Additive manufacturing has the potential to transform the world in ways no one could have imagined when the first pass of a laser managed to solidify liquid into hard plastic.

Although many of these experiments may lead to discoveries decades from now, researchers are using additive manufacturing to test strategies for rejuvenating

the Earth's resources today, using designs such as the artificial reef shown in Figure 8-10. The reef, fabricated from synthetic rock or concrete, will test colonization by natural coral and measure marine biodiversity over time. Such efforts may lead to technologies that can help repair natural reefs damaged by human activity.

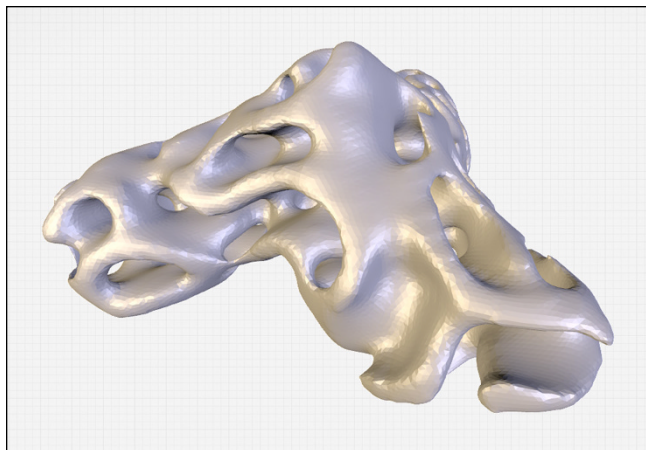


FIGURE 8-10:
A 3D rendering of
a reef.

Creating Medical Opportunities

3D printing is making many new medical inventions possible. One promising area is personalized manufacturing that uses nonbioreactive materials configured for use in biocompatible matrices that do not affect the living tissues.

The first medical applications of 3D printing were external appliances and prosthetics designed to improve the lives of their recipients. Doctors are already using implants such as jawbones and skull protective plates to assist those under their care. Soon, 3D printers will provide custom pharmacology for patients, mixing each day's dose of medicines to meet each patient's treatment and recovery protocols.

Perhaps the most innovative area of medical research is bioprinting: creating living tissues and organs from carefully layered cells that are allowed to grow into the desired form. Currently, patients in need of organs may pass away before compatible matches are found; many others must endure a lifetime of antirejection drugs. Bioprinted structures, however, could be made from an individual's own cells, eliminating issues of availability and rejection.

Researchers are developing techniques for organ replacement that incorporate 3D printing. Surgeons would make small orthoscopic-type incisions to remove the failed organ and construct the new organ within the patient's body to reduce secondary injury from the surgery, which would reduce surgical risk and speed recovery.

The first simple tissues were layered without structure, but tiny blood vessels have been successfully 3D-printed by means of sugar frameworks around which the cells bind together. More recently, complex organs such as the liver have been fabricated from donor cells in layered configurations that provide the necessary complex filtering. These technologies are not yet ready for market, but 3D-printed stents (expanding tubes that hold open constricted blood vessels) and simple artificial structures that treat trachea and kidney conditions are being tested in patients today.

The field of bioprinting is experiencing tremendous change almost daily, with researchers vying to capture key patents that will drive the development of surgical products for decades. (Competition is so strong that several labs that originally expressed interest in having their technologies illustrated in this book had to back out to prevent competitors from duplicating their intellectual property.) Researchers around the world are racing to be the first to patent a 3D-printed heart and other achievements. Bioprinting is one area of 3D printing that's unlikely to offer many open-source designs for quite some time. For an example of an open-source bioprinter see this link: www.instructables.com/OPEN-SOURCE-BIOPRINTER/

4 Employing Personal 3D-Printing Devices

IN THIS PART . . .

Explore examples of artistic creation made possible by 3D printers.

See how individuals make use of this exciting technology in both home and small business settings.

Review the needs and considerations you should make before deciding on a desktop 3D printer and determine what you need a 3D printer for.

Take a look at the different types of machines, print methods, and coordinate systems in available 3D printers.

- » Creating clothing and accessories
- » Crafting customized equipment
- » Expressing individualism in design
- » Bringing the abstract to life

Chapter 9

Exploring 3D-Printed Artwork

Additive manufacturing offers many new techniques for creating interlocking components or objects with complex interior structures, and it's no surprise that creative minds find the printed objects attractive. These techniques allow artists to create designs or structures too complicated to be created through traditional means.

This chapter provides a window into some artistic creations made possible through 3D printing — from personal designs a few centimeters long to multistory sculptures for outdoor display. The artists discussed in this chapter graciously allowed me to include illustrations of their designs, and many have shared them for download by others. Where possible, I indicate the sources so that you can try some of these works on your 3D printer, or maybe you'll be inspired to create some 3D-printed art yourself.

Adorning the Body

Among the first types of 3D-printed adornment are personalized jewelry and plastic-based clothing, matching design and visual appeal to individual taste and preference. The customer selects the virtual model as well as the material used to

fabricate the physical form. In Chapter 6, I discuss the experimental virtual storefront of artist Asher Nahmias (Dizingof), where he offered his mathematically inspired designs for sale through Ponoko (www.ponoko.com) in gold, silver, and other materials.

Figure 9-1 shows an online storefront shared by multiple designers, where physical objects and some virtual 3D models can be purchased for download for local fabrication, such as shoes and 3D-printed clothing. Commercial vendors use the same technologies to design custom-fit athletic apparel, reducing the weight of items or adding features not available in traditionally manufactured alternatives. Because a runner's shoes can now be 3D-printed with cleats and structural elements placed according to the way the runner moves, shoes can be reduced to minimal weight and offer a perfect fit, all in the name of providing a fractional competitive advantage.

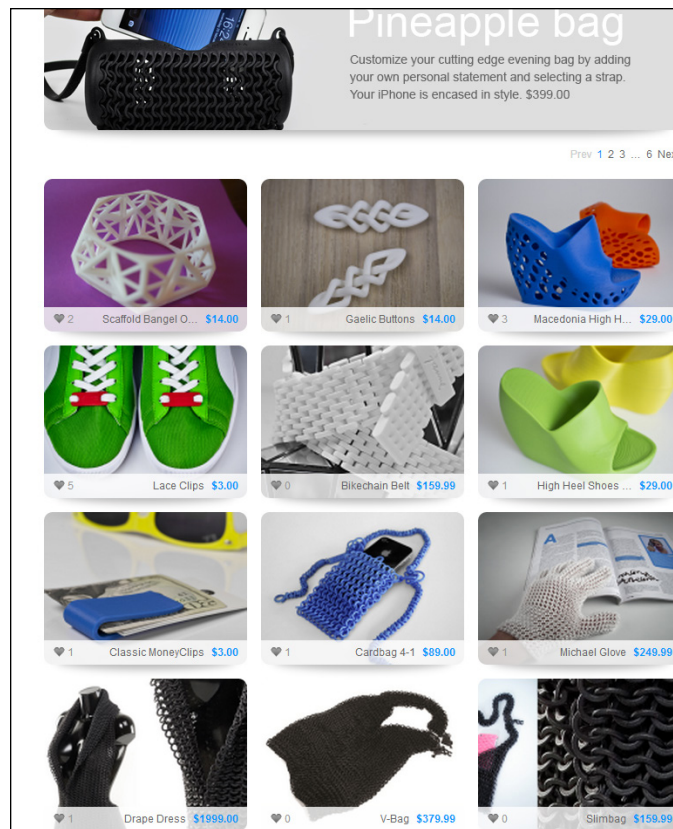


FIGURE 9-1:
An online storefront for 3D-printed fashion.

Personalizing Your Environment

Today's craftspeople and artists can take advantage of additive manufacturing to customize their tools to fit individual body dimensions and preferences.

Figure 9-2 shows several 3D-printed guitar bodies created by Olaf Diegel, who can personalize a guitar body for a performer's arm and finger length, as well as any aesthetic preference. These items can be created to match a band's style or marketing efforts to promote the band's music or brand.



FIGURE 9-2:
Olaf Diegel's
custom
3D-printed guitar
bodies for fully
functional electric
instruments.

Also, abstract information can be fabricated in solid form to personalize the environment. Using 3D-printing systems, you can create custom-curved, biologically inspired shapes for dwellings and outdoor statues, such as the treelike form shown in Figure 9-3.

3D printing offers the potential to customize the human body as well. When the field of bioprinting matures, new trades and services may offer replacement body parts, printing replacements for failing organs or even improvements for muscles or limbs. When actors can transform their appearance to fit a particular role or athletes can add new muscle and connective tissues, legal systems will have to develop new methods of regulations and identity management.

FIGURE 9-3:
A 3D-printed
artistic outdoor
statue design.



Image courtesy of Francis Bitonti Studios

Incorporating Individualism in Design

In past eras, craftsmen chiseled stone or carved wood to create items unique in form and function. Mass manufacturing replaced this labor-intensive process by fabricating large numbers of goods quickly enough to serve a massively expanding population, but at the cost of unique features common in earlier designs. Many older buildings illustrate this development. Gargoyles and other decorative features adorn their walls, even in locations not easily visible to passersby. Today's architectural slab-construction is undoubtedly faster, but those small details have been discarded as unnecessary affectations.

With the development of 3D printers, we can return to a less “slab-fab” world and return artistic expression to designs. 3D printers might even be used to fabricate replacement gargoyles to sit atop buildings' rooflines, restoring and preserving the unique artistry of each building.

Figure 9-4 shows vases produced from tie-dyed nylon filament, based on my own designs and others shared on Thingiverse. The choices of local fabricators make each vase unique in form and color. Integrating personal preferences into new creations creates a unique environment, changing the mass-produced, one-size-fits-all world.



FIGURE 9-4:
Richard's tie-dyed
nylon vases.

It is possible that even more unique changes to the design may be integrated into our mechanisms, such as the delightful experimental design for a research submarine known as the Octopod (see Figure 9-5), designed by Sean Charlesworth. It's a biomimetic (biolike) design for an underwater recovery and salvage vehicle, inspired by the animal that performs a similar type of exploration. Borrowing from nature allows new designs to take advantage of generations of specialization, affording new qualities not present in traditional alternatives.

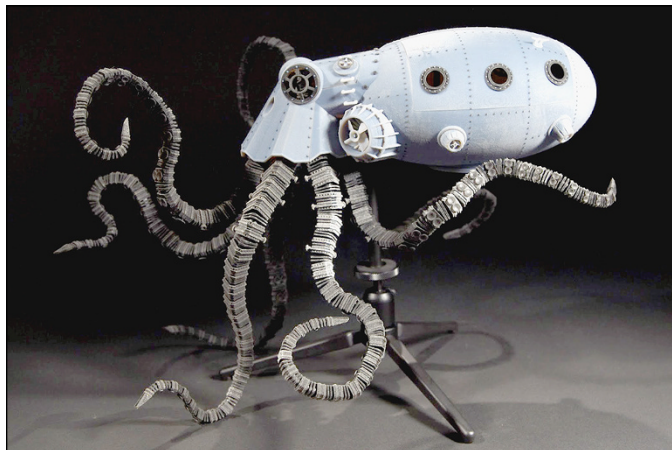


FIGURE 9-5:
The Octopod
underwater
recovery and
salvage vehicle.

Image courtesy of Sean Charlesworth/Charlesworth Dynamics

Visualizing the Abstract

3D printing is a magnificent medium for artistic expression because it allows abstract ideas to be represented in solid form. Difficult concepts become easier to understand than simple descriptions and flat illustrations would allow.

Mathematical models are amazingly detailed and fluid in their representation. Designs like those of Asher Nahmias (Dizingof) and Stijn van der Linden (Virtox) can transform simple equations into elegant works of art. (See Figure 9-6.)

The Sugar Lab also uses mathematical models to create edible creations formed from granular sugars (see Figure 9-7) — examples of new options for personalizing food products through additive manufacturing.



FIGURE 9-6: Mathematically inspired 3D-printable objects originally obtained from Thingiverse.

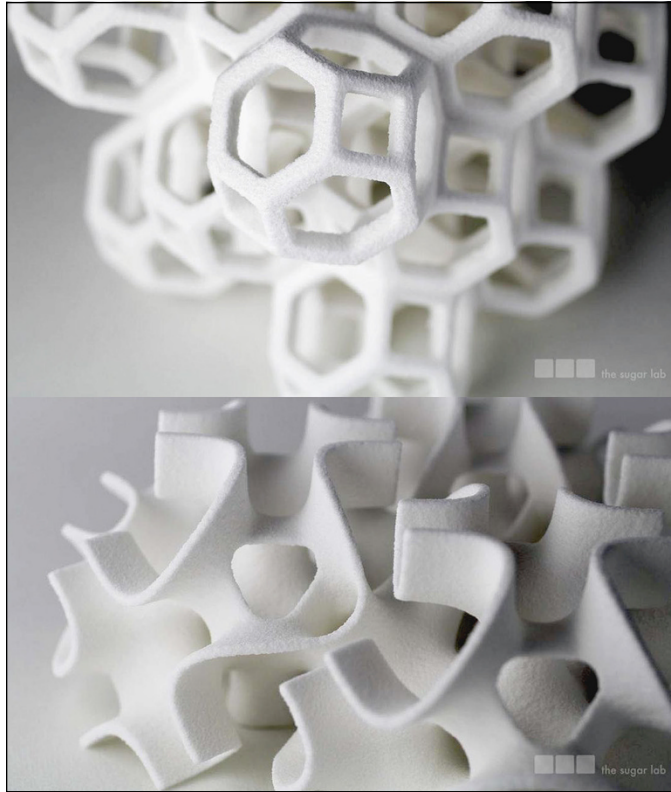


FIGURE 9-7:
Edible math art.

Image courtesy of the Sugar Lab

Sharing Art

Sharing 3D-printable objects can offer ways for artists to engage with the public in the creation of crowdsourced art, such as the PrintToPeer effort created by Jeff de Boer (www.printtopeer.com/sculpture), a Canadian artist known for his 3D-printed designs inspired by armor such as chain, scale, and plate mail. de Boer has created a site to facilitate his artwork where individuals can create their own personalized designs for each scale and then print copies.

Many community-based projects and commemorative designs often bring individuals together, both to celebrate and promote a good cause. This book is dedicated to the life of Sanjay Mortimer and a foundation established in his memory. Many individuals from all around the world each 3D-printed a message onto a hexagon tile, joining together at the E3D headquarters in the UK. For more on this initiative, check out <https://e3d-online.com/blogs/news/remembering-sanjay-one-year-on>.

One practical use of sharing art is to build momentum within the 3D-printing community. Many designers and 3D artists make their work available for people to download for free or purchase as a digital 3D model for printing at home. Louise Driggers modeled a wonderful singing serpent called Adalinda (one of my favorite 3D models), and you can see that I printed an enormous version of this serpent in Chapter 16 to help demonstrate joining multiple part models together — yes, it’s really big. (See Figure 16-22.) This model was so popular on release that many people in the 3D-printing community at the time decided to have a “dragonoff” contest to print the most interesting version of this model. Some were elaborately colored; many were also slightly modified to add features to the design; and a few ended up being printed as tiny as possible, just 10 percent of the original size (13mm tall). I had some printed in translucent materials with added lighting. One was printed and modified to include a fire-breathing mechanism using gas and a spark lighter to flame on demand. The entire contest was a celebration of both the wonderful design and capabilities of both 3D printers and their users to innovate and also show off.

You can read all about the wonderful 2015 dragonoff contest on my blog post at <https://richrap.blogspot.com/2015/11/dragonoff-3d-print-competition-2015.html>.



TIP

Art may serve a purpose beyond artistic value, so I encourage you to design whatever your ideas suggest and collect 3D models you enjoy. If the license allows, print copies of these models and hand them out to spread the word about additive manufacturing. If you want someone to call you for more information, simply include your name and contact information in the object you print. It costs no more to create an object with a customized message than it does to print one without personalization.

IN THIS CHAPTER

- » Exploring Cartesian 3D printers
- » Reviewing Delta options and polar fabrication
- » Seeing SCARA and robot arm motion
- » Working with CoreXY printers
- » Evaluating endless belt 3D printing
- » Preparing for new alternatives
- » Using flexible materials
- » Looking at edible printing
- » Exploring beyond RepRap
- » Considering low-cost alternatives

Chapter **10**

Considering Consumer-Level Desktop 3D Printers

Commercial 3D printing systems have many materials and fabrication techniques still under intellectual property protection, but the earliest types of additive manufacturing processes — such as stereolithography (SLA), fused filament fabrication (FFF), and fused deposition modeling (FDM) — have passed into the public domain. FFF/FDM 3D printers are growing in number; vendors,

specialty shops, and online giants such as Amazon.com now offer a wide range of 3D printers in hundreds of configurations at varying prices. Materials for 3D printers are also big business; demand for rolls of filament and resin formulations is rising each year. Attempts to use proprietary cartridges have not succeeded, which allows companies around the world to develop a more open standard of materials. A price point is available for almost everyone to get involved in desktop 3D printing; this chapter examines the types of 3D printers you can obtain or build for yourself, starting from around \$150 to over \$3,000.

Examining Cartesian 3D Printers

The first desktop 3D printer variation — the RepRap Darwin, shown in Figure 10-1 — uses FFF/FDM to fashion objects from melted thermoplastic formed into a round filament wire. The filament could be fed steadily into the extruder’s hot-end, which melted the plastic as it was added, one layer at a time, to the solid object being formed.

The Darwin printer (like many of its derivatives) resembles a commercial overhead crane, moving the extruder in a rigid framework above the build plate, lowering one layer at a time as the object is constructed. In its simplest form, the extruder applies melted thermoplastic within an area defined by X -, Y -, and Z -axis Cartesian coordinates (see Figure 10-2).



TECHNICAL
STUFF

The Cartesian coordinate system is named for the French mathematician and philosopher René Descartes. His system is used to describe any location in 3D space by measuring the distance in three dimensions from an origin point. For a 3D printer, that origin point represents the home location of the extruder and build plate.

The example shown in Figure 10-2 is like the RepRap Prusa I3 and MINI designs discussed in Chapters 11 through 15. It involves an extruder moving on the X axis along a rigid frame that’s elevated on the Z axis one layer at a time, while a motor performs the Y axis movement by sliding the build plate below the extruder. Like the original Darwin, other Cartesian designs move the extruder via a rigid gantry that provides both X -axis and Y -axis movements, while the build plate itself is lowered one layer’s height at a time and doesn’t otherwise move. This strategy is also used by polar 3D printers, which I discuss in the “Understanding polar Fabrication” section later in this chapter.

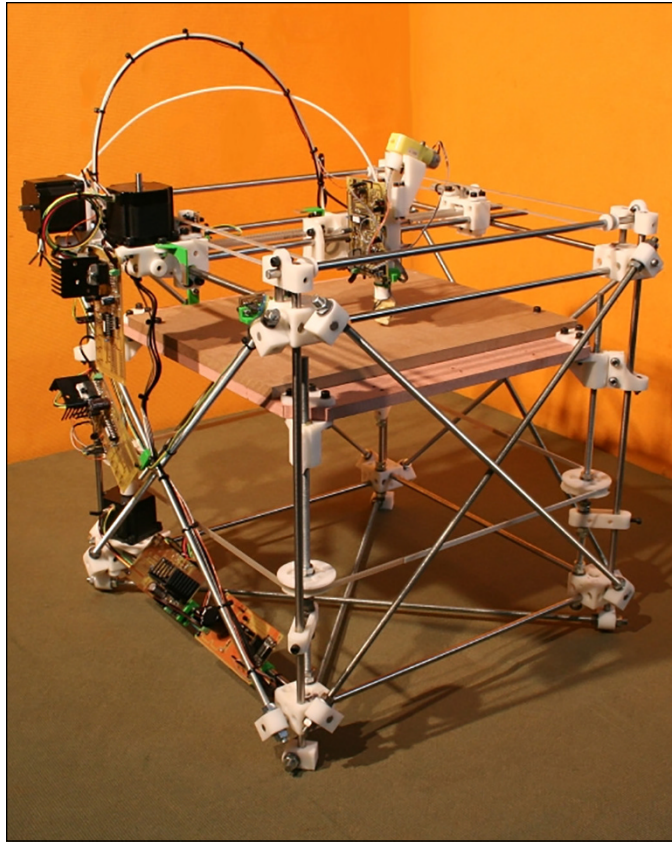


FIGURE 10-1:
The first
consumer-level
RepRap 3D
printer: the
Darwin.

CharlesC / Wikimedia Commons / CC BY-SA 3.0

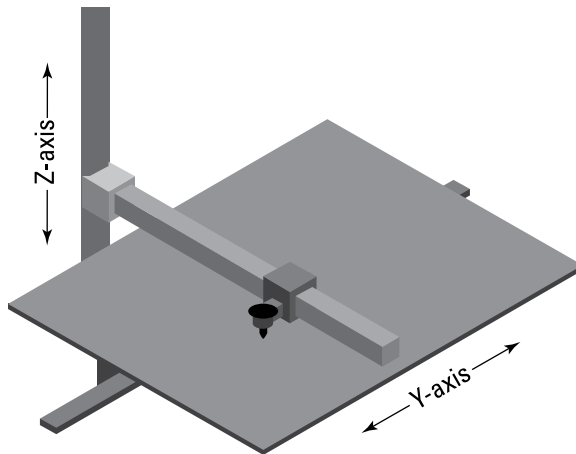


FIGURE 10-2:
A Cartesian-style
3D printer creates
objects by moving
the extruder
(hot-end) in three
dimensions.

Whether the build plate is lowered or the extruder framework is raised, the overall volume available to Cartesian format printers is a box limited by the framework's maximum span along each axis, as illustrated in Figure 10-3. You can scale up a Cartesian system to larger volumes by extending and reinforcing the framing and upgrading to larger, more powerful motors and motor controllers.

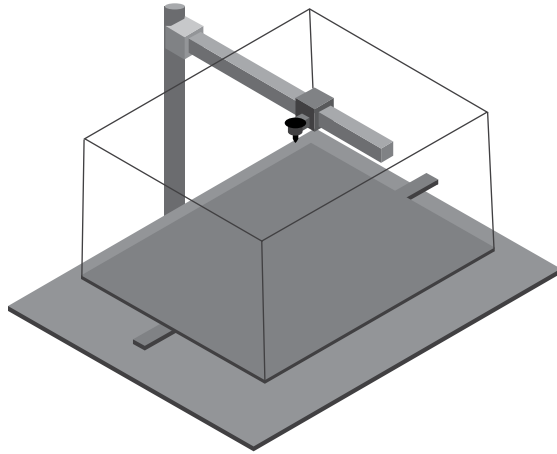
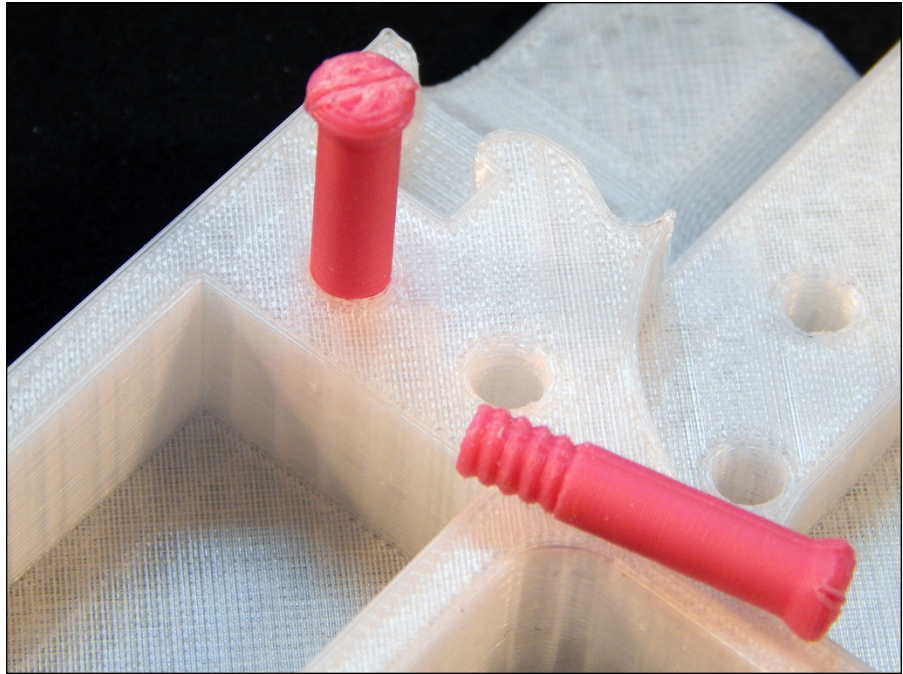


FIGURE 10-3:
The available
build volume for
a Cartesian-style
3D printer.

Oversize FFF/FDM thermoplastic-extrusion printers are often equipped with larger extruder nozzles, limiting individual layer resolution in favor of faster print jobs.

Any objects that exceed the build volume's capacity can be scaled down to fit in the available space, or their design can be cut into pieces for assembly after fabrication. Many techniques can be used to link separated parts from clips and spaces for magnets to threaded holes for screw assembly, like the ones shown in Figure 10-4. Even traditional adhesives and resins can be used to join 3D-printed components to achieve assemblies larger than the build volume of an available printer. (See Chapter 16 for examples and advice of how to join multiple 3D-printed parts together.)

FIGURE 10-4: Components of this nonfunctional 3D-printed firearm are held together with 3D-printed screws that match threads built into the model itself.



Exploring Delta Options

Another strategy used to create 3D-printed objects is based on the techniques used for Delta-style robots, which move in 3D space by moving connections along separate parallel frame components. In this technique, movement relies on multiple frames attached via linkages to a rigid central extruder (as shown in Figure 10-5). The three carriages (A, B, and C) are connected to the central point where the hot-end extruder nozzle is located, and the printer moves them up and down. The hot-end is positioned by triangulation in 3D space (X, Y, and Z). The required print position and the opposite movement (Delta) of the extruder can be calculated mathematically by the printer's control electronics.

Examples of Delta-format printers include the Rostock Max and my open-source 3DR design. (See Figure 10-6.)



TECHNICAL
STUFF

My red, white, and blue printer is an open-source RepRap design shared via GitHub and available on my blog at <http://richrap.blogspot.com>.

FIGURE 10-5: As the frame sliders in a Delta printer move up and down, the extruder moves along all three axes of motion.

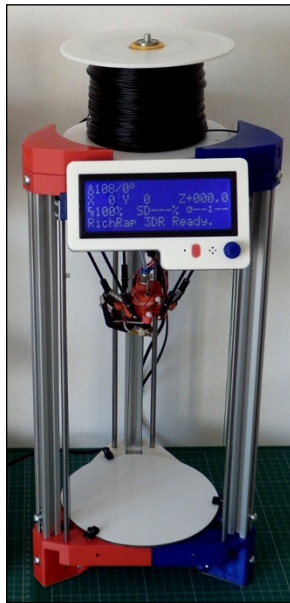
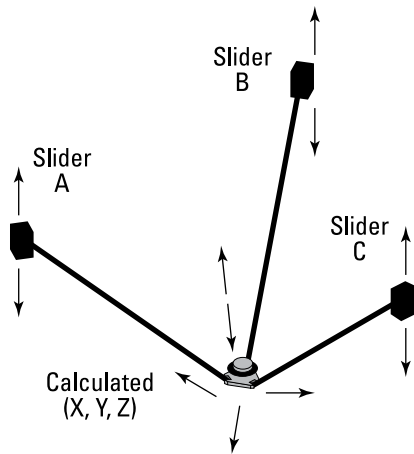


FIGURE 10-6: The Delta-style 3DR printer designed by the author.

Delta printers rely on simpler frameworks than their Cartesian cousins because the electronics provide all three movements along the X, Y, and Z axes; the transit uses the same motors. No separate systems exist for moving the extruder and build plate independently within a rigid framework.

Because FFF/FDM printers rely on the adhesion of layers of melted thermoplastic rather than gravity to hold down successive layers, some designs can be operated upside down without changing the print quality. This configuration is being explored by NASA in microgravity, using an FFF/FDM printer on the International Space Station in orbit around the Earth.

Some people describe Delta-style printers as being fun to watch because they're always in motion, whether the extruder is being raised or lowered, transferred along a flat plane, or transferred between any two locations in 3D space. The length of the linkages between the sliders and the extruder mount limits the build volume, which at its highest point must still fit below the extruder and within the support framework. Although technically a triangular space, the build volume for most Delta-style printers is represented by a tall cylinder above the build plate, as shown in Figure 10-7. Objects can be built so long as all elements fit within the virtual cylindrical volume. Many RepRap Delta 3D printers have linkages that allow access beyond the triangular edge, but many designs provide slightly smaller build volume to reduce the mechanical components needed for the slider's linkages. With a circular print envelope, it's a wonderful machine to print vases; some of the ceramic or clay 3D printers use the Delta arrangement for exactly this purpose.

For more general information about Delta printers, check out RepRap's wiki page at <https://reprap.org/wiki/Delta>. As for specific designs, the following list highlights some examples:

- » **3DR:** <https://reprap.org/wiki/3DR>
- » **Fisher:** <https://reprap.org/wiki/Fisher>
- » **Simpson:** <https://reprap.org/wiki/Simpson>
- » **MicroDelta:** https://reprap.org/wiki/Micro_Delta
- » **Hangprinter:** <https://reprap.org/wiki/Hangprinter>
- » **Rostock:** <https://reprap.org/wiki/Rostock>

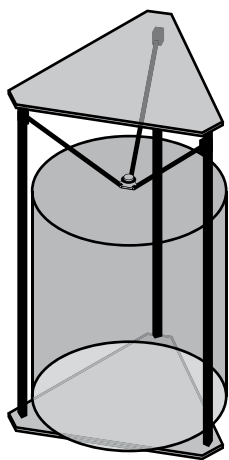


FIGURE 10-7: Possible build volume for a Delta-style 3D printer.

A Delta-style printer doesn't rely on its framework to support the increasing weight of the printed object, so it can be made from lightweight metals such as aluminum or locally available structural materials such as bamboo. Like all RepRaps, Delta-style printers can be equipped with FFF/FDM thermoplastic hot-end extruders (like the one shown in Figure 10-8) or with gel or paste extruders for other purposes. Figure 10-8 shows a standard lightweight FFF/FDM extruder hot-end, which would be fed plastic filament incrementally by the extruder's stepper motor mounted on the fixed frame of the Delta printer. The thicker wires provide power to the heating element; the smaller wires report temperature measurement back to the electronics from a small thermocouple. Reducing the weight of any fast-moving print heads is much more important on a Delta-style machine; you are, therefore, less likely to see the extruder motor and a full metal hot-end and extruder on this type of machine.



FIGURE 10-8:
A standard
J-head-style FFF/
FDM extruder
hot-end.

Based on the weight of the extruder and the print material, Delta-style printers can be controlled by toothed belts, lightweight chains, or even braided fishing line to connect each slider with its associated motor.

Understanding polar Fabrication

A third technique for moving the extruder within a 3D volume involves rotating either the build plate or the extruder's support around a central point to build a single layer. This type of design, based on the polar coordinate system described by Greek astronomers and astrologers, relies on rotation around a fixed pole (like the Cartesian system) and measurement of the distance along a radius or ray from that pole at an angle θ to represent the measure of rotation. If you know the pole's location, the angle θ , and the measure of the radius from an axis running through that pole, you can define any point in a flat plane by using the polar coordinate system.

Figure 10-9 shows a true polar 3D printer, which uses a rotating build plate over which the extruder is placed and can move along in the X axis (front to back). The combined rotation of the build surface (imagine a potter's wheel) and the front-to-back motion allows the extruder to be positioned anywhere on the build platform. The height (Z axis) can then be altered by lowering the rotating build surface or the moving X axis. Some problems need to be overcome with the rotational motion. One full rotation of the object, however, results in distortion due to adhesive drag of the melted thermoplastic as the build plate revolves around the pole. Other alternatives place the extruder's framework through the center of the build plate, but this arrangement requires more complex mechanical connections and makes leveling more difficult.

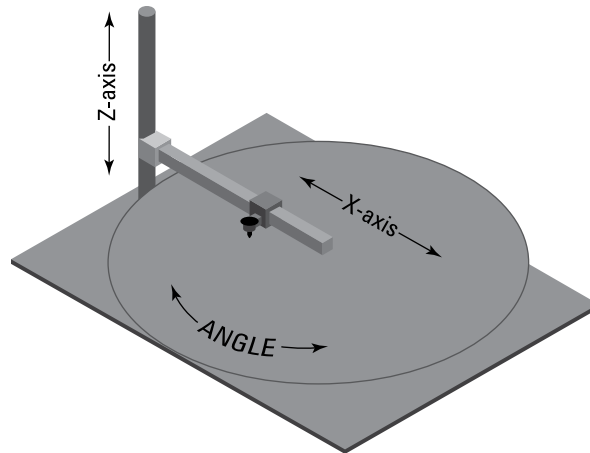


FIGURE 10-9:
A true polar-style
3D printer.

Getting to Know SCARA and Robot Arm Motion

Similar to polar fabrication but without a rotating platform, the Selective Compliance Assembly Robot Arm (SCARA) motion system is similar to the movement of a human or robot arm. In the polar system, the arm moves in and out; the SCARA arm can move both in and out and left to right. A multipart arm rotates around a common pole. (See Figure 10-10.) An example of a basic SCARA-designed 3D printer was conceived by South African engineer Quentin Harley, who named his RepRap printer Morgan.

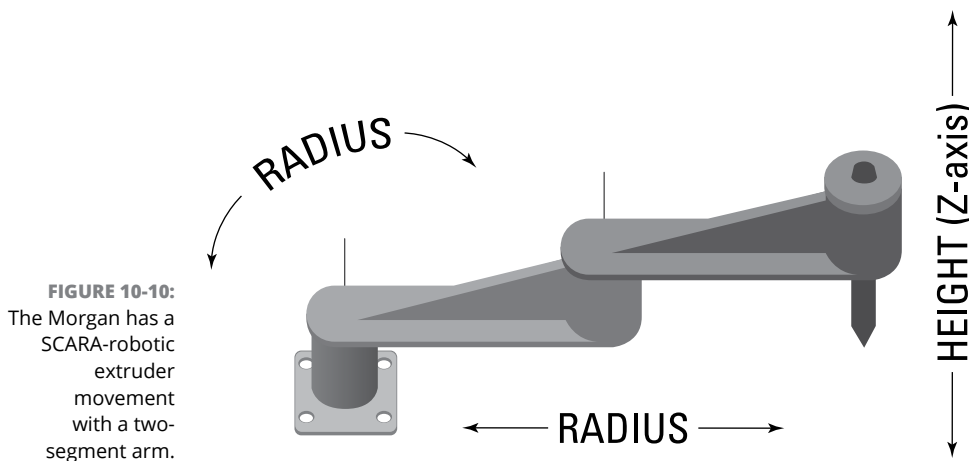


FIGURE 10-10: The Morgan has a SCARA-robotic extruder movement with a two-segment arm.

By using an articulated arm and a stable build plate, this design avoids the difficulties of a true polar system because the object needs to drop only one layer at a time — just like some Cartesian systems — without the need to operate in a full circular path around the pole. Because the object being printed drops down only and doesn't rotate, the printer exerts no twisting force on the object, so no torque is transferred due to the cohesion of melted thermoplastic.



REMEMBER

To reduce the complexity of mechanical support elements, the SCARA polar design only uses part of the possible full circle around the central pole. Its build volume is typically limited to a half-circle or less, leaving room for structural support to either side of the build plate. Any object can be built so long as all elements fit within the virtual half cylinder's area.

More SCARA-based positioning systems are being developed and used for 3D printing and various forms of additive manufacturing. The SCARA system is ideal for applications such as food printing (see “Sampling 3D Food Printers” later in

this chapter). Picture an arm extending from a wall or machine to a plate or other container. An accompanying camera vision system could then allow for accurate printing of food or sauces on the plate or container, which can be in any position with any rotation.

CoreXY – High Speed FDM 3D Printing

With a CoreXY arrangement, the left-right (X -) and front-back (Y -) axis movement are fitted at the top of the machine; both can move the print head to any point on the build surface. This arrangement allows for a lightweight print head and fast-moving carriages to improve speed and print quality. The bed only has to move slowly up and down for each printed layer; the frame can be made of strong solid materials, and the Z -axis bed can also be made very rigid to improve vertical layer stacking and overall print quality.

To keep a lightweight moving print head, some CoreXY machines use a Bowden tube extruder so the weight of the extruder motor can be fixed at the back of the machine while a constrained PTFE tube feeds the filament into the print head. This arrangement has a few negative aspects, but overall allows for a well-balanced machine. (For more on the principles behind CoreXY printers, check out RepRaps' wiki page at <https://reprap.org/wiki/CoreXY>.)

CoreXY – Voron2

One of the most popular CoreXY 3D printers is the Voron2, a machine which opts for extruded aluminum sections when it comes to the frame. Although it should definitely be considered a modern RepRap, the Voron2 still requires assembly and setup using multiple 3D-printed parts to build the machine. The Voron team have produced an exceptional manual for assembly and detailed instructions for configuration, and the Voron2 project has a very active Discord and Reddit community to assist with calibration and use. This is definitely a project you will want to investigate and, if you are feeling adventurous, it's a great machine to build and use. (For more on the Voron2, check out <http://vorondesign.com/voron2.4>.)

Tool-changing 3D printing

The next step up from CoreXY 3D printers is a tool-changing machine. Most tool changers still use a CoreXY system, but they also allow the tool head to be docked and selected from a choice of two to five or more. These tool heads can be a different color material, a different type of plastic, or even a tool that can auto-insert mechanical components or other parts during a 3D print.

One of the first platforms for tool changing was produced by E3D. Their tool-changer was designed as a reference design for other manufacturers to adapt and design similar systems for the wider 3D printing market. E3D are keen to demonstrate that their extruders and hot-ends used on the tool-changer can form the basis of a multi-tool-based 3D printer. (For more on their approach, check out <https://e3d-online.com/pages/toolchanger>.)

RIDING THAT ENDLESS HIGHWAY WITH ENDLESS BELT 3D PRINTING

Another interesting development in desktop 3D printers is the infinite bed or belt printer. This is a machine in which the Y axis is replaced with a flexible belt as the print surface; you can start printing a full-length prop sword, and as long as you support the end of the model (usually with a number of rollers), you can go on printing the full length, even though the machine is only a fraction of the size of the object. These machines are great for props, cosplay, and general modelmaking during which you need a large solid model that's very often going to be post-processed anyway after printing. These machines can also be wonderful for production of smaller parts as they just keep on dropping off the end of the belt until you have printed an entire run. One of the most popular endless belt printers is the Creality CR30 Printmill. At around \$1,200, it's well worth investigating if you need to print long parts like model scenery or multiple production parts one after another. The CR30 was originally project launched on the crowdfunding site Kickstarter and was successfully engineered and promoted by technology legend Naomi Wu for Creality. The CR30 can now be found for sale online at various stores and resellers. The CR30 was a more commercially evolved design that had technical input from the earlier open-source WhiteKnight project by Nak3DDesigns.

The Prusa XL is one of the first desktop multi-tool head 3D printers to reach the market. A large machine, it lets you use five different print heads during a multi-print process. As you'd expect for a large and complex machine, they do come at a higher price point of around \$5,000. Certainly not an entry-level machine, but for complex production of multi-material or multi-color objects, it's a viable option for consideration. (If a Prusa XL sounds intriguing, check out <https://www.prusa3d.com/product/original-prusa-xl-7/>.)

Building Emerging Alternatives

In addition to FFF/FDM variations on the popular open-source RepRap printer, many affordable consumer-grade alternatives are available — from the open-source Fab@Home paste- or gel-extrusion design to the proprietary Form1 SLA system. Community-designed open-source hardware and software designs have become part of many consumer-level designs, as discussed in Chapter 11.

As more patents on the fundamental intellectual property for additive manufacturing expire, many alternatives will be developed. Legions of hobbyist designers are following the example of the founder of the first open-source 3D Printer (RepRap) design, Dr. Adrian Bowyer, an engineer, mathematician, and former academic lecturer at the University of Bath in the United Kingdom. Fundamental laser-sintering patents have now expired. Open-source alternatives to other, more proprietary designs that use granular binding are already being explored, such as the Pwdr 1 printer. (See Figure 10-11.)

The Pwdr's open-source design is based on common inkjet printers. The machine applies a liquid binder to fine granular powder held in one hopper, which is then transferred via a roller to create successive layers in the build chamber on the other side. Some patents for this design are still protected intellectual property; a Pwdr kit or printer can't yet be sold to consumers, but its designers are working on a design that individual hobbyists can use as soon as more of the patents holding back commercial sales expire.

Some early signs point to a faster fabrication process enabled by advanced chemical research. Liquid resin-based formulations can be manipulated by the introduction of gases such as oxygen through permeable membranes to speed the reaction from liquid to solid. Removing heat from this faster process is a challenge, as is the tendency for a rapidly cured material to stick to the membrane rather than to the previously cured resin layer. These advancements and others like it will improve the next generation of 3D-printing systems.

New materials and methods allow the use of alternative technologies for 3D printing. One exciting development is the use of daylight-sensitive liquid resins. (Daylight sensitive is almost any wavelength of light that does not need to be ultraviolet — so the sun, an LED torch or lightbulb, even your smartphone screen can affect daylight-sensitive liquid resins.) Many existing SLA printers use an ultraviolet (UV) laser or reflected Digital Light Processing (DLP) projection system to cure UV-sensitive liquid resin, layer after layer. Material advancements and higher quality optical displays are speeding this process, so high-resolution models can be manufactured quickly and in a wide range of materials.

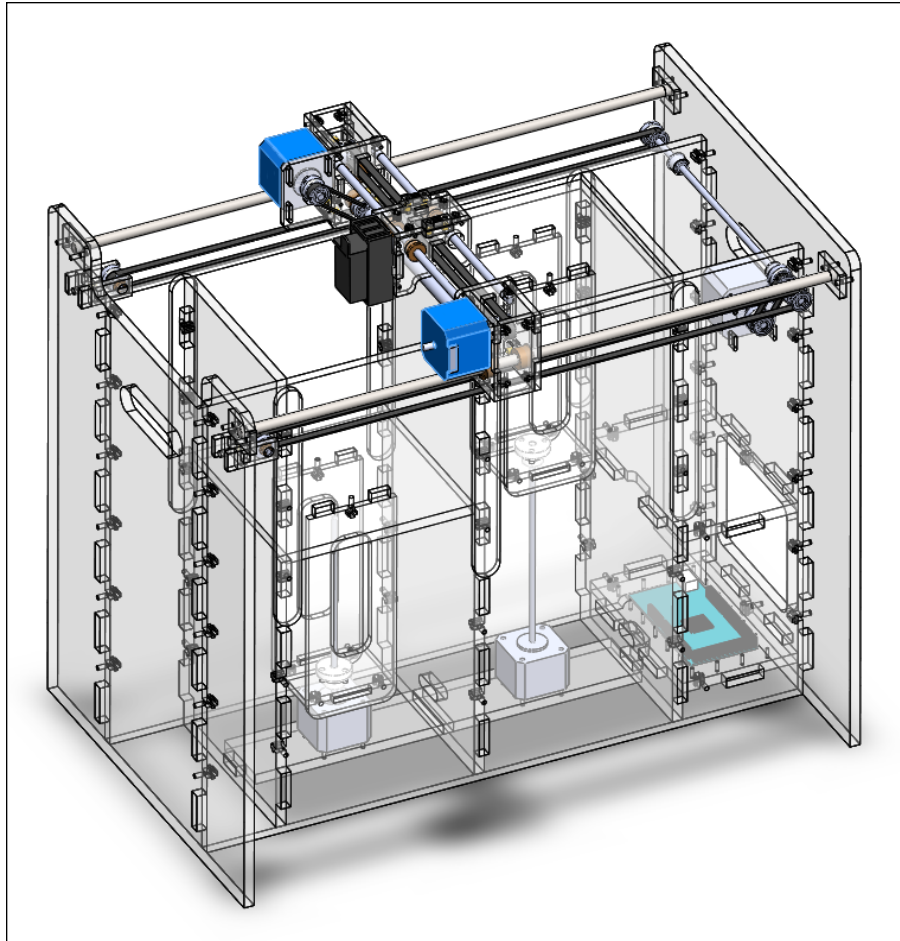


FIGURE 10-11:
A rendering of
the open-source
Pwdr granular-
binding 3D
printer in
development.

As an alternative to UV resins, daylight-cured materials allow a tablet or smartphone screen to be directly used to cure the resin. The screen displays a slice of a 3D object. After each layer is exposed, the screen is positioned slightly farther away. A 3D object appears to grow out of the liquid. These machines are a little tricky to set up, as you must not accidentally expose the liquid resin to a source of daylight. Also, if you have to give up your smartphone or tablet for hours at a time, it's unlikely to catch on. Nevertheless, with recent advancements in very high-resolution LCD screens for tablet computers and other mobile devices, manufacturers have used this screen technology, combined with high intensity UV back-lighting, to produce lower cost SLA printers. Many now start out priced at under \$200.



REMEMBER

Significant challenges remain before these materials can be easily handled and used in small compact machines. Resins often heat during the curing reaction process, for example. With some daylight resin formulations, quite a fast thermal reaction can occur in direct sunlight. The more this reaction is slowed, the longer it takes to produce a 3D object from resins.

Another challenge is that almost every display device produces a different level of light. Depending on screen size, you may not get the 1:1 scale model you expect. The size of an image layer on the screen can be calibrated as part of the setup process so you achieve the correct dimensioned part, but calibration is another hurdle for a device that's often sold as a simple-to-use alternative to existing 3D printing methods.



WARNING

Many SLA (resin)-based 3D printers are available for sale, with a significant number at such a low price point. Price pressures mean that manufacturers are starting to experiment with different resin formulations. However, a word of caution is called for here; if you are considering buying and using a resin-based 3D printer, please do as much research as you can into the resin materials used, the print enclosure, and the configuration of any part of the machine that is likely to be exposed to resin. A significantly higher level of safety protection equipment is required along with ventilation and chemicals to wash and finish curing your resin 3D prints. Given these facts, I would strongly recommend that you don't go with a resin-based 3D printer as your first machine. If you do choose to do so, keep in mind that you should never touch uncured or semi-cured resin; it can pass through your skin and become embedded into your body. You may also develop a hypersensitivity to many resins if you are exposed to them or their fumes over time. I do not consider any resin-based 3D printer suitable for desktop 3D printing at home or in an office environment.

Working with Open Innovation and Community Designs

3D printers tend to get significantly more expensive with larger print-size capability; they also take up much more space. Some innovative open-source RepRap designs allow for giant 3D prints at a lower cost than most common desktop 3D printer kits can produce.

One example is the Hangprinter (see Figure 10-12), designed by Torbjørn Ludvigsen. This floating 3D printer is suspended in midair as the print motion is driven by winding and unwinding fishing line. The print surface can be almost anything that fits on the floor. Maximum dimensions are limited by how far you can run the cables to hang the machine. The design consists of mostly 3D-printed

components, so if you already have a 3D printer, you can fabricate this project to make occasional giant prints. All the files and information you need to build this printer are at <https://github.com/tobbelobb/hangprinter>.

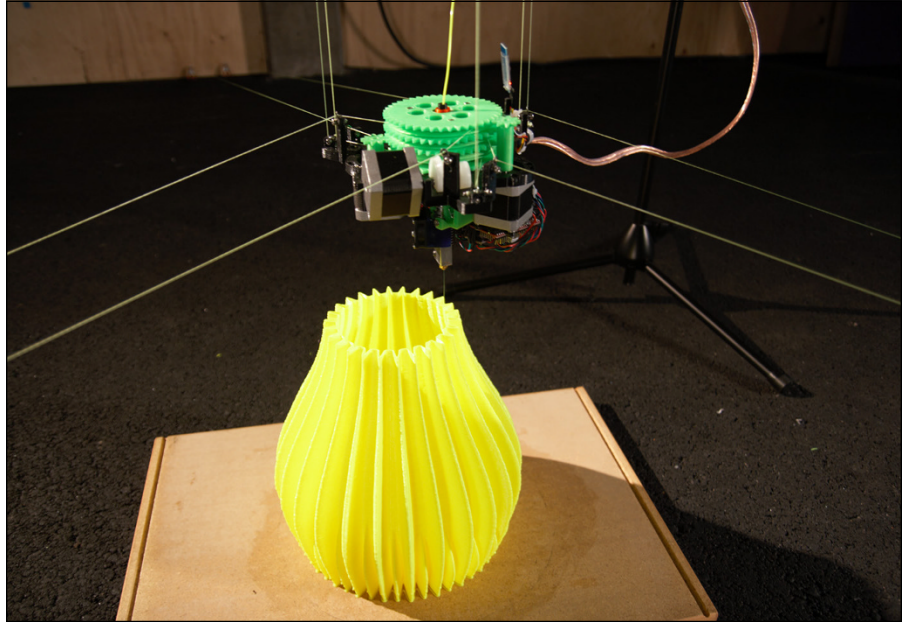


FIGURE 10-12:
The RepRap Hangprinter allows large-scale 3D printing without the need for a structural outer frame.

Image courtesy of Torbjørn Ludvigsen

New 3D-printing technologies are being presented for sale on crowdfunding sites or as preorders for products being developed. These crowdfunding sites are just what inventors and startup companies need to get their products introduced to a wide, eager market. However, using these sites can also be a roller-coaster ride for both backers and creators. Many successful crowdfunded 3D-printing projects have occurred over the past few years, but the results are often disappointing. In some cases, no product is ever shipped to waiting backers, or the product is ready years after the expected completion date.



WARNING

Be careful about what you're funding, backing, or investing in. Supporting new development is good, but don't think of this support as ordering a product with an exact specification or a firm delivery date. If you need a 3D printer to be productive right away, you'll be better served by selecting one that already exists and has been reviewed well by seasoned members of the global 3D-printing community.

Examining Printers for More Flexible Materials

To highlight some recent material and device innovations (as well as the limits of current desktop 3D printers), this section takes a deeper look at the trickier aspects of flexible plastic printing. Let's get the bad news out of the way right off the bat:

Printing with flexible filament materials is one of the trickiest things to do with a desktop 3D printer.

Understanding Shore ratings

Material manufacturers and suppliers try to inform customers about the properties of the material they are providing. For many of the flexible materials now available (such as soft elastic, rubber, urethane, and nylon materials), you may see Shore Durometer numbers. A Shore value describes the hardness of a material.

The Shore Durometer hardness scale is most often classified as Shore A or D. Just be aware that there is more than one classification of elastic material.

For further information on Shore ratings, see https://en.wikipedia.org/wiki/Shore_durometer.



REMEMBER

Different classifications have no direct relation, so make sure that you're talking about the same A or D scale if you're trying to compare materials between suppliers.

An elastic band, for example, is likely to have a Shore 30A rating, meaning that it's very soft and likely to stretch many times before breaking. A gel saddle seat for a bicycle often has a Shore rating lower than 15A, meaning that it's extremely soft and highly deforming — gel-like indeed. The tread on your car has a Shore rating of 70A or higher. A solid plastic product, such as a high-density polyethylene hard hat, has a Shore rating around 75D.

The Shore rating is a good way to understand whether you're buying a stiff or flexible filament, which helps you understand what type of compatible extruder you need to push flexible material into your printer's hot-end.

Flexible 3D printing filaments from manufacturers such as Ninjaflex and Filaflex provide a Shore rating for their materials, which gives you some indication of the materials' capability.

Printing with soft filaments

Flexible filaments don't like to be pushed down a feeder tube or squashed by a metal drive gear into an idler bearing; they tend to buckle and compress. When melted, they ooze and expand. For this reason, many new extruder and hot-end designs have been developed with flexible materials in mind. The key thing to look out for is a short and well constrained (tight) path all along the drive mechanism.

The DyzeXtruder design (see Figure 10-13) supports soft filament along its entire length. A set of two drive gears grips and firmly pushes the filament, and the slippery PTFE tube goes all the way down to the nozzle, allowing flexible materials to slide down with less tendency to compress or buckle.

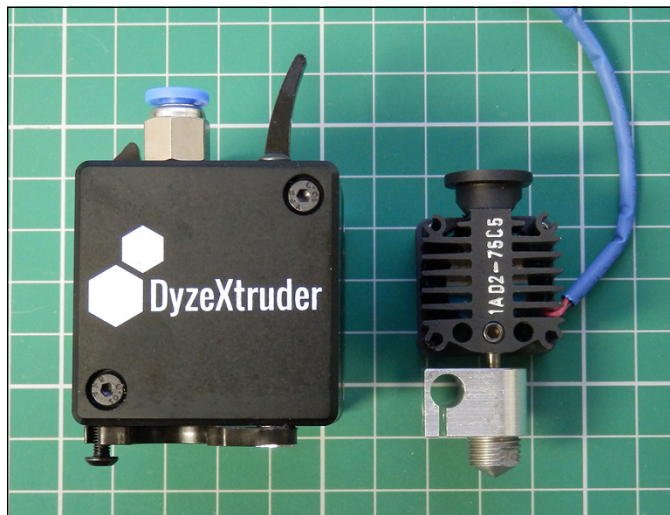


FIGURE 10-13: The DyzeXtruder has dual gears that grip soft filaments and guide them straight down into the hot-end.

The speed at which you can print softer materials may be limited. The time it takes depends on the setup, the type of your extruder, and the hot-end, but expect printing to take half the time (or less) than printing with solid materials such as polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS).



REMEMBER

One common reason why people fail in printing with flexible materials is that they attempt to print too quickly. Start at 25mm per second. Make sure that everything is working reliably and doesn't fail halfway into a print at low speed. Then experiment with speeding things up, if your extruder can handle higher speed.



WARNING

If your hot-end has a Teflon tube that extends all the way into the heating zone, make sure that you never exceed the manufacturer's recommended temperature limits for the hot-end — often, 250 ° C. A slippery Teflon tube can be a benefit for some materials, but it imposes a temperature limit. Often, you see all-metal

hot-ends that don't use Teflon tubes; instead, they have highly polished stainless-steel tubes. What's most appropriate depends on the type of materials you use and the speeds you want to achieve.



TIP

As I mention earlier in this chapter, 3D printing with flexible materials is a tricky process to master. If you want to do this on a regular basis, ask the manufacturer of your 3D printer for advice. The manufacturer may recommend specific settings or upgrades (such as a different extrusion system) to help you to get the best results from the material and finished 3D print.

Flexible materials are widely used in prosthetic and robotics industries. The ability to 3D-print soft and flexible parts makes individual customization quicker and more repeatable than is possible in traditional processes. Figure 10-14, for example, shows an example of such a customized product — a 3D-printed soft shoe insole.



FIGURE 10-14:
3D-printed soft
shoe insole.



TIP

Online 3D applications such as Gensole (www.gensole.com) enable you to create a custom-fit 3D model of a shoe insole for home printing with flexible filaments.

Sampling 3D Food Printers

Significant and fun advancements have occurred in 3D food printing in recent years as more food-based 3D printing systems are developed and used. 3D food printing has become a real alternative to manual cake decoration and precise food plating, as well as many other artistic food presentation tasks previously performed by hand.

The food industry is nowhere near the point of atomic-level replication in 3D printing, so current food printing consists of little more than squirting pastes into shapes. A seemingly endless variety of materials can be extruded, from chocolate to horseradish.

Why does anyone need or want 3D food printing? Processing a carrot into mush and then forming it back into the shape of a carrot via 3D printing may sound like a complete waste of time and energy. It's easy to dismiss current attempts at 3D food printing as being pointless. But when you consider that food processing is already a common manufacturing procedure, 3D-printing food makes more sense.

One very good reason to 3D-print food is that some people find it difficult to eat the original/solid form of certain foods. Also, hospitals, nursing homes, and even top restaurants could benefit from 3D-printed food, because fresh ingredients, vitamin and mineral supplements, texture, shape, and size could be customized for every meal, taste, or dietary requirement. Realizing this vision is going to take considerable time and effort, but it may be one of the only ways to feed and care for the generations to come.



REMEMBER

3D printing doesn't mean making food out of thin air. The base materials still have to be grown, processed, and transported. Final design, preparation, and cooking could be performed by an advanced cooker/3D-printer hybrid system.

3D food printing won't replace regular cooking, just as other types of 3D printing won't be used for all manufacturing. It's simply another way to process and deliver a customized product.

Top chefs and restaurants are experimenting with 3D-printed food. (See Figure 10-15.) Some like being able to ensure perfect placement of sauce or puree on every plate. Others use it for presentation and to produce foods that would be almost impossible to make by hand (or it would be too time-consuming to do it).

If you want to jump right into experimenting with 3D food printing at home, the Cocoa Press 3D printer (see Figure 10-16) is a great choice for learning more about printing models in edible chocolate. The Cocoa Press system was designed by Ellie Rose during many years of experimentation and multiple prototype machines before the Cocoa Press was ready to use.



REMEMBER

Printing in chocolate sounds straightforward, but it's actually one of the trickiest materials to consider using in a 3D printer. Traditionally, chocolate is tempered and worked to the exact temperature for molding chocolates or casting onto perfect bars with a shine and a snap. Using a layered 3D-print process is not something that chocolate wants to be doing. Chocolate has a very low melting point, and it also takes a long time to solidify. I have made my own extruders in the past

for chocolate, and I know how tricky it was trying to set up many different configurations just to print a chocolate bunny for my daughter.



FIGURE 10-15: Restaurants are producing 3D-printed foods such as this chickpea appetizer.

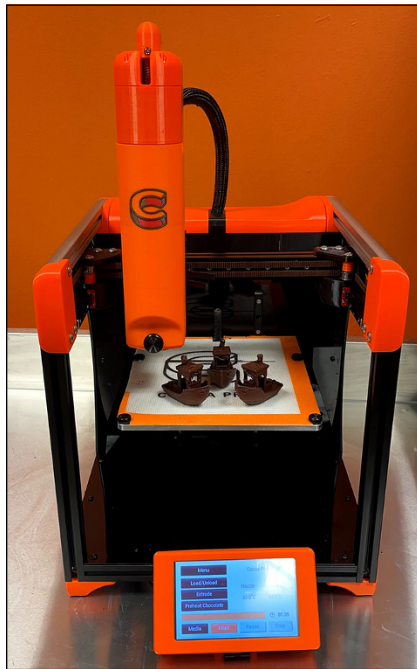


FIGURE 10-16: The Cocoa Press Chocolate 3D printer allows you to make intricate models in edible chocolate.

Courtesy of Eliana Weinstein; Cocoa Press.com

The Cocoa Press printer processes 3D models in ways quite similar to any FDM plastic extruder; it's still cut into layers with an infill density, for example. (Picture having honeycomb infill Easter eggs.) The build volume is 140mm × 150mm × 150mm, and each container has around 70 grams of chocolate ready to print. The machine can be bought as a DIY self-assembly kit that takes around 10 hours to build or as a pro ready-assembled version. Ellie Rose has certainly achieved one of the most difficult and sought-after crafts by designing the Cocoa Press and the results speak for themselves. (See Figure 10-17.)



FIGURE 10-17:
Cocoa Press
Chocolate
articulated fish
creation, ready to
enjoy or be part
of a spectacular
edible display,
designed by
MakeltMichael.

Courtesy of Eliana Weinstein; Cocoa Press.com - Pepito the fish 3D model design by MakeltMichael

Other syringe-based systems are available, but they tend to focus on paste materials rather than solid chocolate or sugar. These types of paste extrusion systems provide a great way to experiment with various paste materials. It's usually a separate syringe-based design that requires only a silicone tube and nozzle to be connected to the moving carriage in place of your normal thermoplastic hot-end extruder. This makes it quite lightweight, so it should be possible to fit onto many different types of 3D printers.

Because the main syringe, tube, and nozzle system can be replaced on many 3D printers, you can easily try printing with many types of food and almost any other substance that can be forced through a tube system. With many 3D printers you can also pause a print, refill, or exchange the syringe and continue printing. There may also be a point where previously deposited layers need to dry or cure before more can be added. This will be true for wetter pastes and silicone gels and some types of food.

The 3D-printed basket shown in Figure 10-18 was originally a full heart-shaped Voronoi-style model designed by Roman Hegglin (Creative Commons license, Thingiverse model 246864). This 3D model was cut in half and scaled up so it could be used as an experimental banneton for baking bread. As the bread rises, it expands and forms the shape of the 3D-printed basket. After baking, the features of the 3D-printed basket are visible in the finished heart-shaped loaf. This is an interesting experiment that shows how 3D-printed tools can work with traditional methods to allow more unique artisan results with minimal effort.



FIGURE 10-18: Sourdough bread allowed to rise in a heart-shaped 3D-printed banneton mold.

Photo courtesy of The Green Bakery

Another use for 3D food printing is for treats like cakes and candy that are often gift items that can be enhanced with personalization. Mini-figure cake topper decorations to bespoke sweets can be 3D-printed using a number of different processes. (See Figure 10-19.) Some use gels that start as liquids and transform into gummy candy, whereas others are made from powdered sugar that has undergone binding.



FIGURE 10-19: Confectioners can produce sweets in custom designs.

Going beyond RepRap

The RepRap project continues to bring innovation to art, design, and manufacturing. In this section, I show how some companies have evolved the RepRap idea into successful products and 3D printers.



REMEMBER

Many of these machines employ traditional manufacturing techniques and custom parts to achieve the demands of mass-volume production, but they all have roots in the RepRap project.

As the fundamental idea of a low-cost desktop 3D printer evolves, it allows more and more people to experience and own this technology for themselves. We see more and more sources of machines, add-ons, and upgrades. Many now do not come directly from the community of users but from companies set up to meet the increasing demand for supply. The following sections take a look at how things are evolving beyond RepRap with machines, software, materials, and components.

Prusa i3 MK3S+ / MK4

The Prusa i3 MK3S+ (see Figure 10-20) is one of the world's most popular desktop 3D printers, available both as a kit and as a ready-assembled machine. It also has one of the strongest links to the RepRap project, and Prusa Chief Executive Officer

Josef Prusa is one of the core RepRap developers. (You get a chance to look at the assembly of a Prusa i3 in Part 5.) The MK3S+ version introduces some enhancements for ease of use and construction and for improved print quality. The Prusa MK4 is another refinement to this printer series, introducing a higher powered electronics platform with the ability to perform input shaping that will help reduce the overall visual surface defects and also allow faster printing.

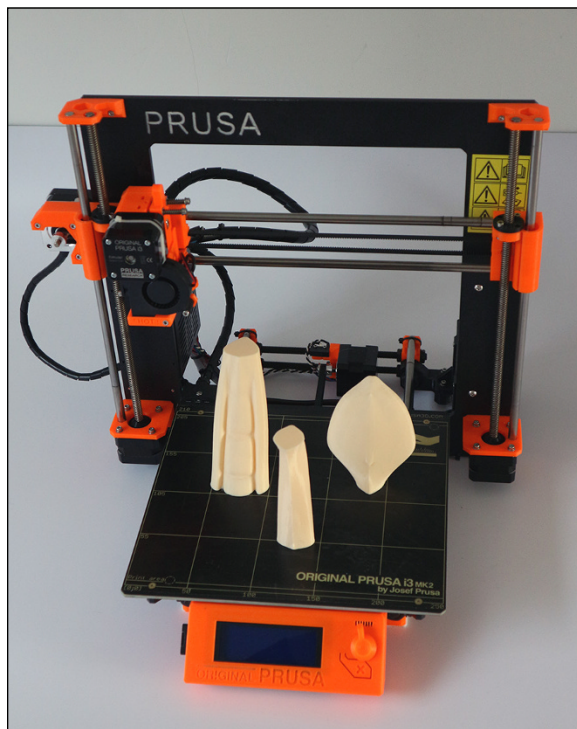


FIGURE 10-20:
The Prusa i3 MK2/ 3/ 3S+ and MK4 3D printer is one of the world's most imitated RepRap 3D printers.

Sigma

BCN3D Technologies in Spain (formerly RepRap Barcelona) offers several RepRap designs as production kits and assembled machines. The company's current 3D printing system is the Sigma R19, which has a small number of 3D-printed parts but is an open-source machine.

The Sigma has dual independent print heads (see Figure 10-21), which allows for two materials or colors to be printed in turn and combined into one model. A support material fitted into one of the two available print heads could be used as a scaffold to enable printing of more complex 3D models.

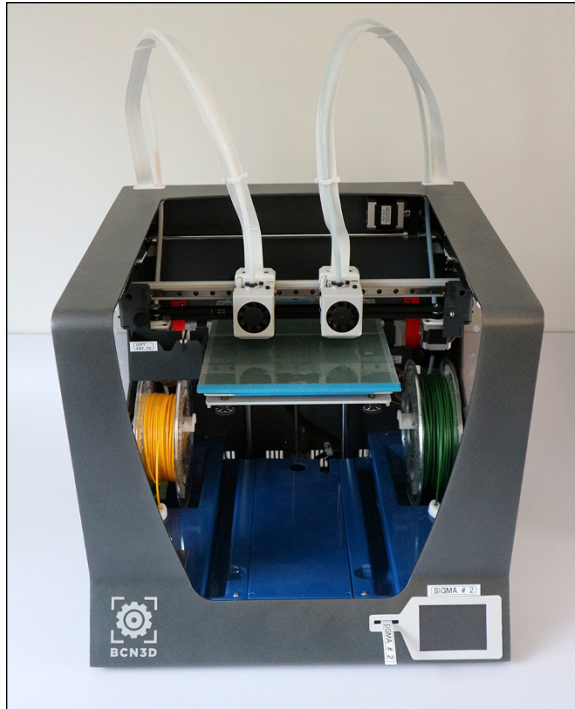


FIGURE 10-21:
The Sigma 3D printer, with dual independent printing heads.



REMEMBER

Two independent print heads mean that one can be parked while the second head applies a different color or material to the model. This arrangement minimizes oozing of material from the inactive head and eliminates the chance that an unused head will knock over or damage previously printed features.

LulzBot Taz 6

The LulzBot Taz 6 serves the desktop and semiprofessional 3D printing market. The Taz 6, shown in Figure 10-22, is a highly evolved RepRap with a metal plate and extruded aluminum sections, as well as a significant number of 3D-printed parts. Features include a large print platform with exchangeable print heads, enclosed electronics and power supply, LCD screen, and SD card slot.

The LulzBot team originally had one of the world's largest 3D print farms, with more than 100 of their own 3D printers running every day to produce parts for their expanding user base worldwide. LulzBot often collaborates with its customers and 3D-printing community to improve, build, and innovate on existing and future developments. In recent years, many more 3D print manufacturers have set up their own 3D print farms to produce components for built machines, 3D printer kits, and upgrades.

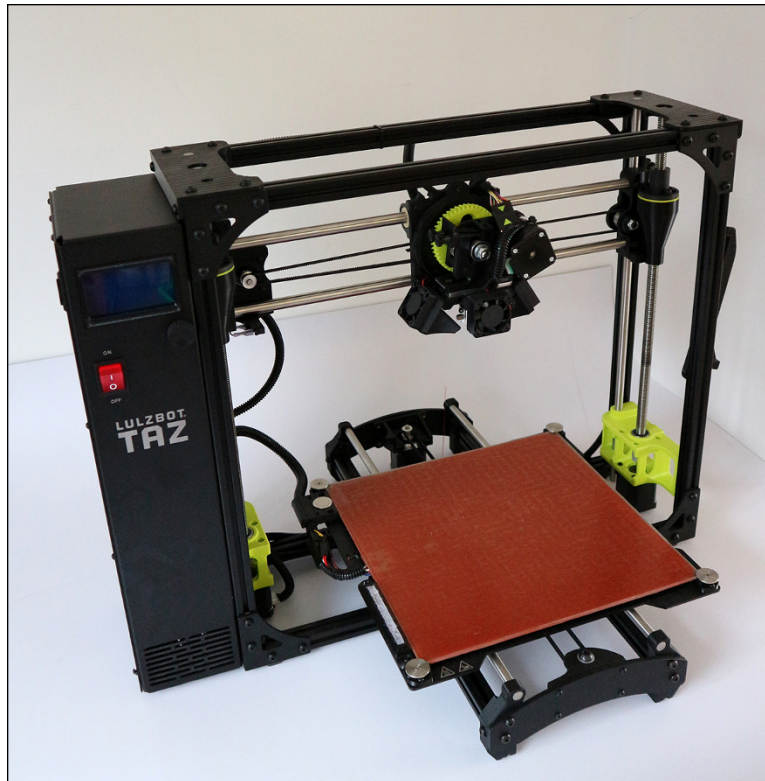


FIGURE 10-22:
The LulzBot Taz 6
3D printer.

LOW-COST ALTERNATIVE 3D PRINTERS

A quick search for 3D printers on Amazon brings up a vast selection of makes and models at a range of prices. In this sidebar, I list a few of the more popular low-cost 3D printers and some of the upgrades you may need to keep these machines running well enough to see whether you want to dive deeper into the world of 3D printers.

- **Creativity:** Here's a Chinese-based manufacturer of 3D printers. Their Ender 3 range of machines has a moving Y build platform similar to the construction of a Mendel or Prusa-style machine. Often selling at around \$200 to \$400, these machines can work well, and most only require a few parts to be bolted together and wired connections made before you are up and running. Some models may have auto bed leveling or a simple manual adjustment.
- **Anycubic:** Another manufacturer based in China, the models in the Anycubic range usually have an extremely low starting price. Anycubic also has a line of resin-based 3D printers. (Please remember my warnings from earlier in the chapter about resin-based 3D printers.)

(continued)

(continued)

- **Flashforge:** Many Flashforge machines are fully enclosed and range in price from a few hundred dollars to right around \$1,000.
- **Elegoo:** Elegoo machines are mostly resin based, but at a very competitive price point; they also offer high resolution and are well constructed. These machines are starting to get good marks for their ability to produce highly detailed models and for jewelry making.

Many more printer models, manufacturers, and distributors are selling low-cost 3D printers — often branded machines from another supplier. As for most purchases these days, be sure to look at the reviews and feedback from buyers, do your own research on sites like YouTube, and read the community questions and answers about any machines you are considering buying.

Keep in mind that, as with other low-cost machines, some corners will have been cut to get the price down. Often this is on-the-frame construction materials or on moving parts like bearings and rails or steel rods where materials of a much lower quality or tolerance get used. This can translate to final prints of a much lower quality, but many of these machines are still very capable of draft-quality prints and can be good starting machines. They will certainly teach you how to repair and service numerous parts and tinker with settings for hours.

One key area that's common to upgrade on low-cost machines is the extruder and hot-end system. If you find yourself having a lot of clogs or jamming of the extruder feeder, then this is the area of 3D-printer components you probably need to upgrade. That said, a good E3D extruder (filament material feeder) and hot-end / nozzle will usually cost more than an entire low-cost machine, so, as the saying goes, you get what you pay for.

- » Evaluating your needs
- » Running a 3D print farm
- » Selecting a design
- » Choosing print materials
- » Identifying key components and software

Chapter **11**

Deciding on a 3D Printer of Your Own

Deciding what type, what size, and how much to spend on a 3D printer can be quite a confusing process. In this section I'll help you evaluate what's important for you in a desktop 3D printer so you can determine whether desktops either a) can deliver what you want or b) are not able to provide what a professional 3D-printing service could produce. If you decide that there is a suitable desktop option for your own 3D printer, I'll fill you in on what you'll need to be aware of and what materials and software will assist you with getting set up for desktop 3D printing.



REMEMBER

You might have noticed that I've mentioned RepRap a number of times in this book. I do so because RepRap is truly a wonderful machine — one that can replicate itself. Its unique design lets you construct an inexpensive 3D printer that can reproduce many of its own components. If you decide that building your own 3D printer is something you want to do, then RepRap is a great place to start. But if you decide to go with a kit or a readymade machine, there are quite a number of 3D-printing manufacturers who are ready, willing, and able to guide you down that path. Some of the machines offered may incorporate elements of RepRap technology; others may just be trying to deliver a low-cost or high-performance 3D printer that's already ready to be used straight out of the box.

The first step is to evaluate what you want to achieve with 3D printing. Do you just want to learn more about an interesting technology firsthand? Is 3D printing just something you want to tinker with? Are you intrigued by the possibility of being able to use a technology that may assist you in a hobby or the development of a new business idea? Whatever you need a 3D printer for, after you've evaluated your needs, I can walk you through the available options.

Evaluating Your 3D Printing Needs

When selecting a 3D printer, it's good to first determine what you plan to do with it. Ask yourself, "What do I need a 3D printer for, and what am I expecting a 3D printer to do for me?" Often, the reply is "I don't need it for anything in particular; I just want one." This answer is absolutely fine. Let's face it — 3D printers are exciting technology and well worth exploring just for the fun of it.



REMEMBER

After you have a 3D printer at home or at the office, I guarantee you will find multiple uses for it. Repairs, fun models, functional objects, and beautiful art are all a few clicks away when you are all set up and ready to 3D-print.

Another common reply is "I want to print parts and sell them." This answer is one that a lot of people use to justify investing the time and money in a machine that can naturally make useful physical parts or artistic objects. One word of caution here: It takes a little time to achieve results good enough to sell, but this goal is a fine one that can drive you forward and the very one that's already helped spread RepRap to every part of the world.



REMEMBER

If you want to design and 3D-print miniature detailed models for hobbies, jewelry, or crafts, there are some suitable machines that can offer highly detailed results, but you may still be disappointed if you compare them to handcrafted or even many mass-manufactured objects.

No single 3D printer can do everything; it's quite common for people to own multiple 3D printers that can handle different material types or have a specific purpose. If you want to print objects the size of a chair, for example, you clearly need a very large machine with a big nozzle. The level of detail may not be so important with a large object, but the print time will be a significant factor, so having a bigger nozzle and powerful extruder that can push a lot of molten plastic may be really quite important if you want to print big or strong functional parts. If, on the other hand, you only want to print jewelry samples and a very high level of detail is critical — and you also don't mind if it seems to take forever for a job to complete — then a resin 3D printer may suit your needs.



3D printers are really good devices for helping you fix a damaged 3D printer, so having a backup machine (even if it's a low spec model) can often help get you back up and running quickly by being able to print out replacement parts.

Do you want an open-source RepRap or another 3D printer?

After assessing your needs, you should work out whether you want just any 3D printer or specifically a RepRap (open-source 3D printer and eco-system). This distinction is important. Due to the demand for 3D printers, many companies have used the open-source RepRap technology to produce machine designs that can be traditionally mass-manufactured. It's ironic that the success of a low-cost self-replicating machine now makes it so hard for manufacturers to keep up with demand that some companies choose to mass-produce parts. This situation leads to a few issues for customers. One problem is that if you can't always reprint some of the parts for your machine, it's harder to upgrade, repair, or self-replicate.

These issues aren't problems, however, if all you want is a 3D printer and have little interest in RepRap's self-replicating or sharing nature. Many machines can fill the bill, and almost all of them started from a RepRap branch or use its core technology. (Some machines' manufacturers still class the machines as RepRaps, whereas others aim to hide those origins.)

RepRap is an open-source and open-community project. This means that all the design files, ideas, and digital documentation is shared as multiple free-to-use projects, even for commercial use. The RepRap community and its technology forms the basis for almost all new home 3D printers. RepRap stays vibrant and ahead of the game because of its diversity and the sheer number of dedicated, loyal users and developers in its worldwide community.

One of the core benefits of RepRap is the total control you have over making changes and enhancements to your printer. People and companies around the world make changes, upgrades, and enhancements of RepRap on a daily basis, so almost any improvement or enhancement you can imagine has already been implemented by one developer or another — someone who has probably made that improvement available to you.

This open-source concept isn't just for machine-based improvements. You can also find upgrades for software, print material settings, and machine firmware (software running on the electronics of the printer), all of which can help you avoid a lot of frustrations. The print material settings in particular are becoming important areas for adjustment and tuning. (See Chapter 15.) Many consumer printer manufacturers, for example, lock down the settings of their printers so

that you can print only with a specified material or at specified speed and quality settings. With a RepRap (or other open-source) 3D printer, however, you can print with simple settings or alter virtually any aspect of the machine. This flexibility becomes really important when you're trying to create adventurous objects or want to print with new or unusual materials.



REMEMBER

Not everyone will want this much control, of course, but pretty much anyone can appreciate the freedom that this flexibility offers. With RepRap, you're not limited by arbitrary manufacturer settings. You're limited only by your own imagination.

What is your 3D printer budget?

It's worth giving some initial consideration to the overall budget you are willing to spend to get set up with a 3D printer. The actual 3D printer is only the start, and that can cost anywhere from just \$150 to more than \$10,000.



TIP

If you are looking for a basic model and you only plan to tinker and see whether 3D printing is an interesting hobby or pastime, then take a look at fully built or mostly assembled kits from a few hundred to five hundred dollars, pounds, or euros.

If you have already started doing research or you read this book and decide that you want to go all-in with 3D printing, it's still well worth considering investing in a lower specification machine to start you off. The reason is that it can be a very steep learning curve for some of the very high-end machines that contain multiple tool extruders and offer many color 3D prints or have the ability to print in a wide range of material types. You can still explore a lot of this with a low-end machine, and it will teach you a lot along the way.



REMEMBER

You will need to buy print materials; these can cost you anywhere from \$5 for a small sample coil to around \$30–\$60 for a 1Kg spool of many standard materials or bottles of resin. Some more adventurous materials such as wood filled, metal filled, and glow-in-the-dark often start at around \$40. More exotic and challenging materials may cost well over \$100 per spool or 1 liter of resin, and several can be upwards of several hundred dollars or more.

You can, however, print a lot of different parts with a 1Kg spool of material, but that's also a problem — if you start to print lots of different parts, it usually means you're likely to need spools of material in multiple colors, types, or special finishes. This can quickly add up to a large investment in stock of plastic or resin and a lot of space to store all your different materials or colors.

Several other parts and tools are also often required; I fill you in on these in more detail later in this chapter.

Do you buy a ready-built 3D printer or assemble a kit?

In the early days of desktop 3D printing, you could often source a kit of individual component parts which were painstakingly assembled into a (hopefully) working machine. Then, after a lot of calibration, setup, and experimentation, you may have something that could 3D-print out objects. Nowadays, you can still buy kit machines that have lots of individual parts that will test your patience upon assembly, but it turns out that the meaning of the word “kit” has evolved. Some of the lowest cost so-called “readymade” models on the market are actually a kit of mostly assembled modules that you put together. It’s not a great deal more difficult than assembling an Ikea set of furniture, so partially assembled readymades should still be a realistic option for you to consider.

So, should you buy a 3D printer or a kit? To answer this question, go back to your reasons for wanting a 3D printer in the first place. If you want to use it as a tool, and the physical output of a model is the only important factor, a fully built commercial machine with backup, support, and training available may be the way to go, but this route is more costly and (as I mention earlier in this chapter) somewhat limits what you can do with the machine. It’s also harder to get online community support, because the commercial models are not always the machines most people in the wider community are using, upgrading, and tinkering with. Thus, fewer people will have a desire to assist you, and to be fair, assisting you with problems is the job of the company that sold you the commercial closed-source machine.

If you are interested in the way a 3D printer operates, then it’s a good idea to consider building up a kit machine or a semi-assembled model. If you’re feeling more adventurous you can source all the parts yourself and build up a custom machine or one of the many open-source RepRap designs. Building a printer yourself is still one of the best options in this phase in the evolution of desktop 3D printing. These machines are still highly mechanical, so parts will wear out; components will require careful calibration; and over the life of your 3D printer, you’ll run into all sorts of problems that interfere with your printing. Consider, however, that these same issues will occur with any 3D printer, no matter the cost; that’s the nature of the technology. For this reason, it’s often better to build your own machine and understand exactly how these parts work together to function as a 3D printer. When you’ve built your machine, you’re in a much better position to repair and maintain it.



TIP

Don’t be too worried. Building a 3D printer from a kit really isn’t as difficult as it may sound. Almost all kits have ready-built electronics and wiring, so your main job is to assemble the mechanical framework, measure and mount parts with nuts and bolts, and then plug all the connections into the electronics control board. If

you do all these things carefully and according to the instructions, building a 3D printer can be a highly rewarding experience.



REMEMBER

The open-source RepRap community extends to every part of the world, and its members come together in many ways. For anyone seeking advice, the best way to get it is to join a local group such as a community makerspace of like-minded individuals. Discord, Reddit, and many forums exist for 3D-printer design and development, tweaks, and tips along with help when things fail; and they will fail. Learning how to 3D-print and use the many available tools, settings, and programs is a lot to take in; it can be a steep curve, but it's well worth the effort. In no time at all, you'll be confident with the technology and could be contributing your own modifications to the RepRap community.

Running a 3D Print Farm

You probably won't be running a 3D print farm straightaway unless you already have some experience with 3D printers. Maybe you (or your company) has decided to invest in a way to mass produce lots of 3D-printed parts in-house and you now need to either set up a farm or run it.

Setting up and running a 3D print farm is quite a straightforward task, but it does require some thought and consideration. In this section, I call on my first-hand experience running a small 3D print farm (around 20 machines) to offer some advice, some tips, and some tricks of the trade. (See Figure 11-1.) All that assembled wisdom should give you some key pointers if you ever need to run even 4 or 5 machines at a time or produce a lot of the same models over and over again. This section also shares a lot of general tips for good printing setup of multiple parts onto a build plate; it's well worth a read even if you have no intention of ever running lots of 3D printers together.



TIP

If you decide to run a 3D print farm, having exactly the same type of machine makes many things easier. That way, you can set up and calibrate all the machines to be almost exactly the same, design and slice your models just once, and then run the same Gcode files on all the machines together. This compatibility can really help if you are producing multiple different parts that all need to fit together or be interchangeable. You may also decide to have a small number of 3D printers configured differently for specific model parts. It's common, for example, for a print farm to have larger nozzles fitted so production can be faster, but you may also require a number of small but detailed parts. Having a few machines with smaller nozzles can provide these more detailed, or different colored objects without slowing down the main farm production.



FIGURE 11-1: A simple small 3D print farm using many identical Prusa i3 MK3S+ machines that can share the same production files and produce identical parts.

Designing models for printing in a farm is probably one of the trickier aspects when it comes to running a farm. If you have ever printed any part over and over again, you probably noticed pretty quickly that a few small changes to the printing process could speed up the print time, make the print more reliable, reduce support material, and print in an orientation where very little postprocessing is required.



WARNING

Safety first. With any type of 3D printing, health and safety is vitally important, but when you're running a 3D print farm, the importance of safety and good working practice is many times more critical. I can't continue to stress enough how important it is that you consider safe work practices. That means keeping the rooms where 3D printers are being used well-ventilated and making sure you have both smoke and fire detection in place. Most importantly, never leave 3D printers unattended when they are on or running.

Before you make any decisions about what type of 3D printer to buy for a 3D print farm, first think about the maximum print time you can allow a set of machines to be running. For example, if you are working an 8-hour day, then you want all machines to finish before you go home. You need time to clean up the workspace and set up the printers for a new run the next morning, and then you need enough time after that to get another set of parts printed again before the end of the next day. Repeat that process a number of times each day, and you'll have a working print farm.



REMEMBER

There is little point in buying many large 3D printers with huge build surfaces if it's going to take multiple days for the prints to be completed. You will be better off buying many more smaller machines and splitting your objects into sets of build plates or even sections that fit back together after printing to form larger objects.

The time duration of a printed object is highly dependent on the print quality settings, the material being used, how large the object is, and its infill density, or you may just want to have multiple objects on the print bed. Luckily, we now have an accurate duration of expected print time in most slicing programs that can really assist to pack the most objects onto a build plate in the time you allowed for machine operation.



TIP

Don't print every object in exactly the same default center location on your print surface. It's quite tempting to allow the parts to be auto-arranged, but if you always print in the same spot you will start to wear out a perfectly good build plate or risk damage to a print surface right in the middle. It's also really good practice to group similar height parts together so the print head has to move less around the build surface to get to each part being printed. That can speed up print times and improve quality.



TIP

It's ideal for a print farm to use quick change build plates and preferably a flexible build surface rather than glass. Such surfaces can be covered by a smooth PEI sheet or a powder-coated PEI textured plate. (See Figure 11-2.) Having multiple sheets cleaned and ready to use will allow quick changeover and almost continuous production printing.

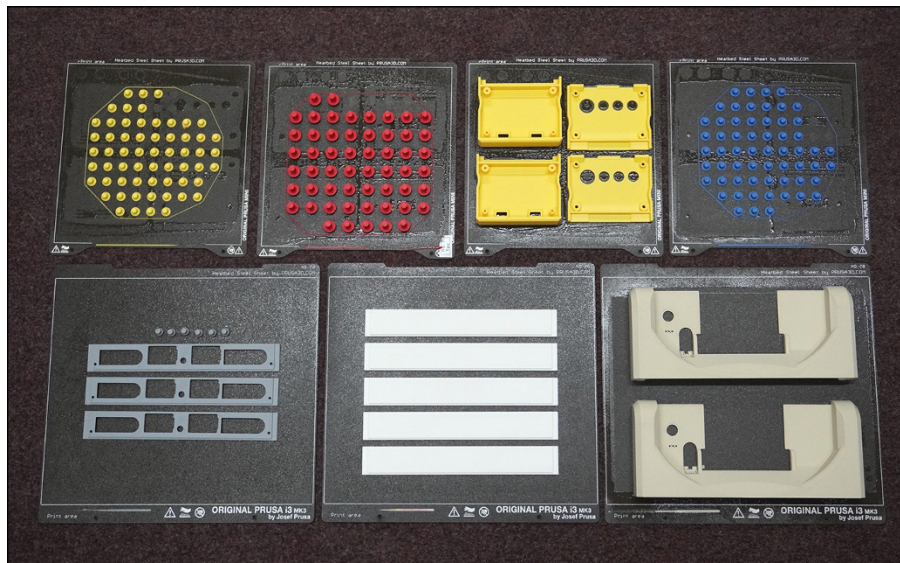


FIGURE 11-2: Two types of 3D print plates — the Prusa MINI (top) and Prusa i3 MK3 flexible magnetic quick-change PEI coated sheets (bottom).



REMEMBER

Regular maintenance is essential with any 3D printer setup, but the heavy usage that comes with a print farm means that component part failures are going to fail and that things will wear out in some cases quite quickly. Depending on how often you are running the 3D print farm, you will need to perform routine checks and maintenance every month. Bearings will wear out anywhere between 6 months and 2 years, and cooling fans may fail at almost any time. Keep your fans clean and check that they are spinning without excessive noise. Any wires that are attached to a moving part of the 3D printer are likely to eventually break or become poorly connected. Having sets of spare parts is an essential part of running a 3D print farm.

Minimizing wasted plastic, reducing the need for support material and its subsequent removal from printed parts, and generally keeping any extra material you need to clean from the build surface at a minimum are good goals when designing parts destined to be printed on a 3D print farm. The more finished you can make a printed object, the less work you will need to do after printing and when it's time to prepare for another print run.

The choice of material is also quite important when talking about using many hundreds or thousands of filament spools. I personally recommend manufacturers who produce filament on sustainable cardboard spools or as a refill coil. (For more on that topic, check out Chapter 16.) Cutting down on single-use plastic waste is not only important, but it'll make your recycling life easier as well. Choosing a filament manufacturer with a high quality tolerance and consistent color from batch to batch will allow you to switch over empty filament spools mid-print and know that you can use multiple parts together without seeing a difference in the tone or color. Whatever you do, please test out materials before you buy a large batch. You may also find that matte finish materials assist with overall finish quality and can also help hide layer lines from the 3D-printing process of stacking layer-on-layer of plastic materials.

For practical 3D-printed parts, PLA and PETG are often more than adequate for many types of objects you may want to use a 3D print farm for. Figure 11-3 shows a range of electronic enclosures printed in PolyTerra matte PLA. All these parts were made on a 3D print farm.



TIP

Consider fitting hardened steel nozzles. I generally recommend fitting a hardened steel nozzle over a standard brass nozzle for almost any desktop 3D printer. Switching to a hardened steel nozzle is essential if you run a print farm. Yes, these nozzles are more expensive, but they take many times longer to wear down than a standard brass nozzle and will help you keep your print farm running more reliably between regular servicing.



FIGURE 11-3:
Range of 3D
printer electronic
enclosures
consisting of
multiple parts.

Licensing and Attribution

RepRap is an open-source project. From the start, it had to be, because trying to limit or stop a machine that can duplicate a significant proportion of itself is an almost-impossible task. The open nature of RepRap provides huge benefits for sharing within the wider community of makers, designers, and users. Even better, this open aspect doesn't limit the project to hobbyists or impair its use with closed-source machines; it does the exact opposite as long as you pay attention to the licenses used.



REMEMBER

Despite the fact that RepRap is open-source, almost all RepRap technology is provided to you under a license. This fact is worth keeping in mind; it could be highly important if you intend to make a business of 3D printing or plan on building on other people's work in this field.

A typical hardware or software license details what you're allowed to do with the files (designs, source code, assembly instructions, and so on) that are made available to you. The core of the RepRap project falls under the GNU General Public License. On the whole, this license means that the files are free and anyone can use them.

You can find the GNU General Public License at <https://www.gnu.org/licenses/gpl.html>.)

The GNU license was designed for open-source software, not hardware projects. That makes using GNU for 3D printers possible but not ideal. This limitation is due to the fact that hardware projects have a physical presence that can be shown out of context from the original project or reused without obvious acknowledgment of the original.

Therefore, many of the hardware elements for RepRap, as well as the associated 3D designs or supporting electronics, are licensed under a Creative Commons license. The brain of most RepRap 3D printers, for example, is an Arduino electronics control board, a modular set of electronics used for all sorts of control projects and industrial tasks around the world. (You can find the Creative Commons licenses at <https://creativecommons.org/licenses/>.)

Arduino controllers are open-source hardware and software, licensed for use with the Creative Commons Attribution-ShareAlike license. This arrangement allows both personal and commercial use, but you must share the files the same way that Arduino does and also credit Arduino in the documentation of your design or changes.

A typical Creative Commons license uses a simple set of icons as a logo to indicate what type of license it is and what you can or can't do with it legally. The license shown in Figure 11-4, for example, allows you to copy, distribute, or transmit the work; you're also free to adapt the work and make commercial use of the work it covers.



FIGURE 11-4:
A typical Creative Commons license icon.

In the logo, the icon of the little person in a circle means that this license is provided on the condition that you attribute the work in the manner specified by the author or licensor, and that you do not do this attribution in a way that suggests or implies that the author has endorsed you or the use of your work.

The SA icon means *share alike*, so all derivative work must be shared under the same license. In this case, the derivative work can also be used commercially. You wouldn't be allowed to build onto this work and then change it to a noncommercial license to stop other people from building on it, for example.



REMEMBER

Keep the following example in mind; a designer has come up with an original design for a 3D model. The designer may want to make the files available for individuals to use but may also want to restrict the model's use for commercial benefit and may not allow derivative work based on the design. This arrangement still allows you to download the 3D model, print it, and use it, but it's licensed only for your own personal use.

The logo in Figure 11-5 specifies that work can be shared but isn't licensed for commercial use (NC) and doesn't allow derivatives (ND). You're still required to attribute the work to the creator or licensor when you share it.



FIGURE 11-5: Icon of a Creative Commons license with more restrictions on commercial use.

If you obtain a 3D model under this license, you're not allowed to sell a 3D-printed version of the model, publish modified versions of the design, or sell the model's design files.

You *can* print and display the model as long as you get permission from the author and make the author aware whether the design or print of the model is helping you sell something else, such as a 3D printer that printed the licensed model. When you do so, it's of the utmost importance to provide attribution to the designer, display the licensed name of the model, and show the license. Then you're complying with the license terms, and the designer gets credit for the design, which is visible to anyone who sees the printed object on display.

When you don't provide attribution, the license system breaks down, and the designer whose work you used this way will be less likely to share the next design (or to be very happy) with you.



REMEMBER

Always be aware of how anything you use or share is licensed, regardless of whether you've paid for it. Even if an item is being given away, there may still be legal restrictions on how you may use it.

Selecting a 3D Printer Design

When selecting a 3D printer design, don't disregard some common RepRap 3D printers. You shouldn't consider these established designs all out of date just because they're not on the cutting edge; consider them to be stable ways to get started, sensible choices, and springboards to further adventures into understanding the history of 3D printing and how current machines are based on similar designs. All the 3D printers discussed in this section are based on established technology and have been widely used in the community. Updated versions of these models would be an excellent choice for your first 3D printer. If you have not yet chosen a 3D printer from the list in Chapter 10, or if you just need a little more background to help you make a decision, here is some further history about the RepRap origins of many desktop 3D printers available today.

RepRap and open-source designs

The evolutionary nature of RepRap is based on survival of the fittest, so many designs, modifications, and upgrades fall out of use or are superseded by newer designs as users and other developers adopt them. Watching a RepRap design grow and change, and even sometimes die out, is one of the joys of an open-source hardware platform.

The following list describes the most common designs for early RepRap 3D printers, in approximate chronological order (subject to innovation):

» **Mendel:** The original Mendel printer was designed by Ed Sells at the University of Bath in the United Kingdom. After the original design (named Darwin after the biologist Charles Darwin who developed the theory of evolution to explain biological change) started replicating at various universities around the world, Mendel set a new standard for RepRap printers that's still strong and used today in many derivative machines. The Mendel concept is Cartesian, much like existing 2D printers or plotters in its operation. As I describe in Chapter 10, most Cartesian-based machines move the print bed back and forth along the Y axis, move the printer carriage from side to side on the X axis, and lift or lower the entire X axis and printing carriage on the Z axis (usually with two motors, one on each side). The original Mendel printer is now considered to be overly complex to build, but modern versions of the Mendel have become popular and account for a high proportion of the RepRap 3D printers built by users.

The Mendel 3D printer is a pain to build. It has around 1,500 individual components and is over-engineered compared to the two following models. It's a good reference point for the technology that blossomed into almost every desktop machine on the market today, but it's just a little too complex to build and run every day.



TIP

- » **Prusa Mendel:** The most widely constructed and widely used RepRap 3D printers are the Prusa Mendel and its many derivatives. (A modified Prusa Mendel is shown in Figure 11-6.) This machine, designed by Josef Prusa, is a simplified version of the original Mendel design that proved to be highly popular. Version 2 of the Prusa Mendel is still built today and is highly recommended as a first machine.
- » **Mendel90:** This machine (see Figure 11-7) is a variant on the Mendel design that has a rigid frame (usually made of laser-cut wood) and plastic acrylic sheet or laminated DIBOND material as the main structural elements rather than the traditional RepRap threaded rods used in the Prusa machines. It uses almost all 3D-printed parts apart from the main structural frame, which is often manufactured from an aluminum-and-plastic DIBOND laminate. Mendel90 was designed by Chris Palmer (also known as Nophead), one of the original RepRap team members. He shares a vast amount of RepRap and 3D-printing information on his Hydraraptor Blog (at <http://hydraraptor.blogspot.com>). This blog is an essential read for anyone who wants to understand the history, challenges, success, and failures of 3D printing at home.
- » **Prusa i3:** The Prusa i3 (MK2/MK3/MK4) has a hybrid design that combines elements from the Mendel90, Wallace, and other machines to make a simple-to-build, high-quality home 3D printer. Version 3, known as i3, is a revised version of Mendel, similar in concept to Mendel90 but with a rigid central wooden, acrylic, or aluminum frame and threaded rods that support the moving bed on the Y axis. (See Figure 11-8.) The Z motors are also positioned at the base as in the Mendel90, which provides Z axis movement with a flexible coupler to create smooth print sides. Overconstraint in previous designs (forcing alignment to a threaded rod that could be bent or worn, rather than allowing for some self-centering freedom on the Z axis vertical movement) often produced Z-wobble, which appeared as bands or grooves on the side of a printed object. The Prusa i3 continues to be updated and improved. (For more on the Prusa i3, see Chapter 12.)
- » **Huxley:** Huxley is a miniature version of the Mendel that uses smaller components (6mm rods for the frame rather than 8mm, for example) and uses smaller 3D-printed parts for its construction. The build area is smaller than the Mendel's but large enough for many applications. The machine is also wonderfully portable. Like the original Mendel, the first Huxley machine was designed by Ed Sells at the University of Bath. Huxley was an unofficial project until it was unveiled to Adrian Bowyer and then published as an official RepRap printer. The Huxley wasn't as popular to start with as its bigger brother Mendel, mainly because many people were trying to build their first 3D printers and opted for the more mature Prusa Mendel design. The Huxley was redesigned by Jean-Marc Giacalone as the eMaker Huxley and sold fast, quickly becoming one of the most popular kits available.

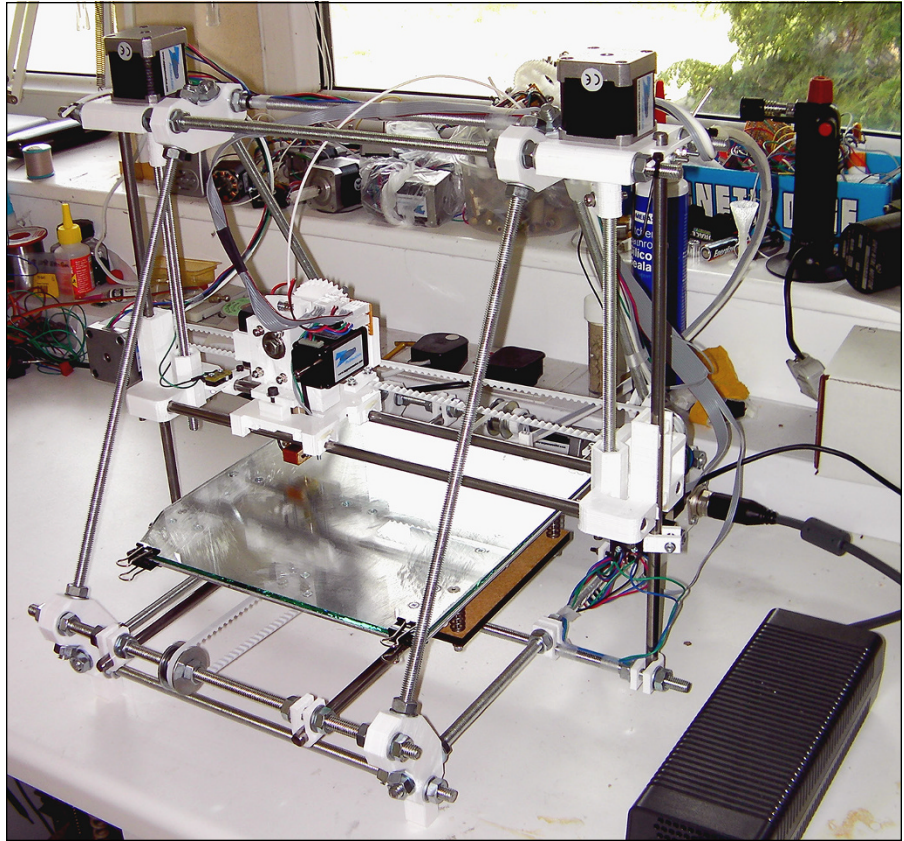


FIGURE 11-6:
Prusa RepRap 3D
printer, Version 2.

Image courtesy of Adrian Bowyer

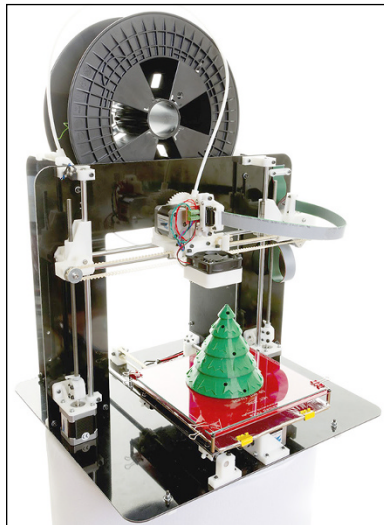


FIGURE 11-7:
A Mendel90
RepRap 3D
printer.

Image courtesy of Alan Ryder

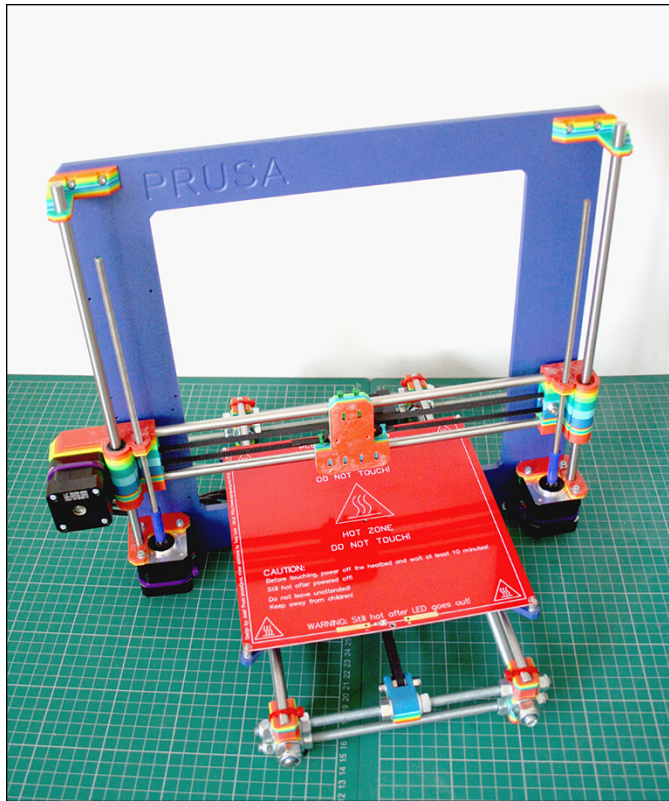


FIGURE 11-8:
The Prusa i3 3D
printer.

» **Wallace/Printrbot:** The Wallace (see Figure 11-9) and the Printrbot have similar configurations. Only the Wallace can be considered a true RepRap, however, because its parts are still produced by printing. The Printrbot's ability to self-replicate has become increasingly more limited. For example, it initially required the use of a wooden laser-cut framework, but it now uses fully stamped and folded sheet metal structures. This approach allowed the production of very low-cost kits and ready-built machines, some specifically designed for educational purposes.

Version 2 of the open-source Printrbot Jr printer, designed by Brook Drumm, is built on RepRap technology and constructed of laser-cut plywood. Due to its mass-manufactured, laser-cut frame, it's one of the least expensive ways to get a home 3D printer. Its motion elements improve its printed output.

The Printrbot can't print another Printrbot. Its intricate, interlocking framework is designed to be cut by a computer numerical control router (CNC) machine or a laser cutter. It can't be easily reproduced by hand, in other words. Wallace, on the other hand, can replicate much of its own structural



REMEMBER

framework and requires only a simple bed-cut square. A RepRap, however, is designed to allow the 3D printer to manufacture the complex parts and have you, the builder, source all other components locally or easily produce them yourself by hand using standard tools or materials. You should not require a tool-shop or manufacturing facility to produce RepRap 3D printers.

Many other RepRap-based designs are available to print out yourself (like my 3DR Delta printer) and even pocket or suitcase printers that can fold flat to store and flip up to allow for a well-sized build area. There are far too many to list here, and, at this point in desktop manufacturing, there is also a very wide choice of ready-made machines that I want to talk about next. If you do, however, want to browse the many different RepRap 3D printer designs, then do take a look at www.reprap.org for more inspiration.

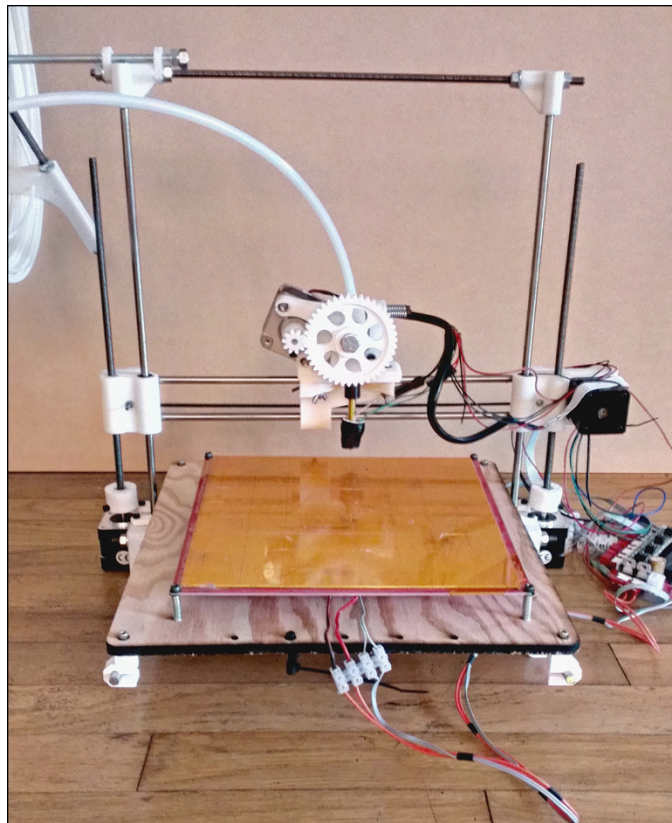


FIGURE 11-9: A RepRap Wallace printer, designed by Rich Cameron as a RepRap 3D-printable version of the Printrobot style of minimal design.

Home 3D printer modular kits and self-sourcing

If building a RepRap 3D printer from raw components and printed parts is not to your liking, a host of home 3D printer modular kits are also available. Whether you want a kit with a lot of ready-made 3D-printer parts or a kit with few of them comes down to budget and personal preference. All the kits use a similar set of RepRap control electronics, firmware, and software slicing programs; all can achieve similarly high-quality print results with a little care and tuning.

Endless variants of Cartesian-based 3D printers are available. All the 3D printers in the following list can provide excellent printed objects; some are available in a modular kit of ready assembled sections that can be bolted together or individual components that will take a little longer to assemble yourself. Most kits will have a good construction manual to assist you and often a large community of users who can lend a hand or provide advice when you get stuck.

- » **Prusa MINI:** This machine is one of the most popular kit form printers; it's small but very capable. An ideal first 3D printer. Available as a kit as well as mostly assembled sections, this machine has a smaller build area, but a lot of great features you may not find on other budget printers listed here. (You get a look at how to assemble and use the Prusa MINI in Chapter 13.)
- » **UltiMaker:** This 3D printer, based on RepRap technology, was one of the first kit machines to be sold. It uses laser-cut wooden panels to make a box frame and has a configuration similar to the early RepRap Darwin. The print bed only moves up and down, and a lightweight print head moves on the X and Y axes. The Ultimaker is not your father's Darwin, however, but a fast printer that introduces a Bowden-fed extruder. This method of plastic extrusion moves the mass of the motor and filament-drive system to a static position on the machine; then the filament being extruded enters a slippery PTFE (Teflon)-based tube that doesn't allow the filament to bend, buckle, or compress. At the other end of this tube (usually, about 500mm long) you find the moving print head and the hot-end that melts the incoming filament being pushed by the remote extruder. This setup allows the very light print head to move very fast indeed to achieve faster printing and potentially higher accuracy compared to a heavier print head and extruder that can't move as quickly. (I talk more about Bowden-fed extruders in the sections that follow.)



REMEMBER

The Ultimaker Version 3 is no longer a RepRap. Success and increased global sales allow for traditional manufacturing methods of injection-molded parts and laser-cut plastic panels. It is, however, one of the highest quality and fastest 3D printers available for the desktop market. Ultimaker 3 also introduces a new concept in removable cartridge-style print heads, which allows for quick

swapping of nozzle sizes and different print materials. Version 2 and Version 3 printers now come as fully assembled machines and are no longer available in kit form.

- » **Prusa i3 MK2:** This 3D printer (see Figure 11-10) is one of the last commercially available kits with significant global sales. It's a great way to get into 3D printing because the assembly experience is enjoyable and educational. Many of the tricky parts are simplified in the MK2, MK3, and MK4 models. When buying a 3D printer kit today, you should receive a highly detailed manual and you're usually not expected to solder or crimp connections. Simply assemble the mechanical parts and wire-up cables to matching connectors and set up software on a PC.
- » **Tantillus:** The Tantillus looks a lot like a miniature Ultimaker, as Figure 11-11 makes clear. This 3D printer was originally designed to be a fully printable machine. In fact, original versions that don't have the laser-cut frame have the highest percentage of printed components used in any RepRap printer. The case frame construction was originally fully 3D-printed. Another version, with a laser-cut acrylic case, was designed as an easier do-it-yourself kit in a successful crowdfunding campaign by Sublime. One unique feature is the use of high-strength fishing line instead of belts to provide the X and Y motion, resulting in a fast-moving machine and high-quality prints.

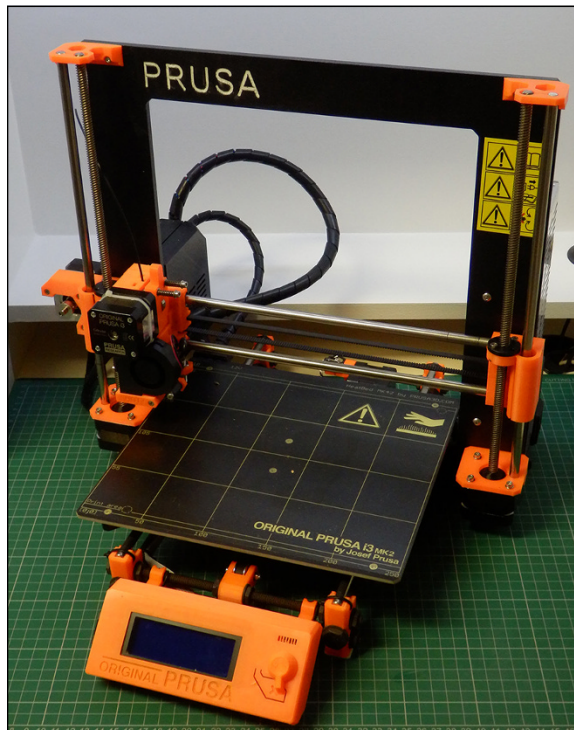


FIGURE 11-10:
The Prusa i3 MK2
3D printer.

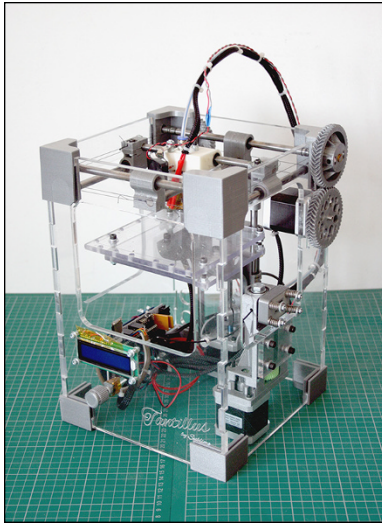


FIGURE 11-11:
The Tantillus 3D
printer.



REMEMBER

Almost all home 3D printers have about the same level of quality and speed, so don't get too hung up on the exact model to choose for your first machine. Especially with a RepRap, you'll be able to upgrade and evolve the design or print most parts for a future model.

Experimental designs

At any given time, the RepRap community has thousands of experimental modifications going on all around the world. Every now and then, a new branch sprouts. New or vastly different machines usually attract a lot of attention, and other developers may have to help refine them into something that can be used across the community.

Open innovation and the development of ideas into physical parts that enhance operation can be one of the most exciting aspects of the RepRap community. The aim in RepRap isn't always to keep making things faster and more accurately; some of the most challenging design improvements come from thinking about lower-cost materials that are more accessible to more people. Other developers seek a new design that occupies less desk space but still prints large objects.

All the designs I've discussed so far in this chapter use the Cartesian coordinate positioning system. The next wave of popular home 3D printers uses the Delta triangulation-based coordinate system, as described in Chapter 10.

Many of the most successful branches of Delta 3D printer designs sprang from a proof of concept machine called the Rostock and an advanced design called the Kossel, designed by Johann C. Rocholl, who also further developed the Delta firmware branch of Marlin that is used in many RepRap Delta printers.

Following are the most popular Delta 3D printer designs:

- » **Rostock Max:** This design (see Figure 11-12) is inspired by the original Rostock but has a laser-cut frame and makes innovative use of bearings that run on aluminum extrusions to provide the linear motion of the machine. It's also one of the biggest machines on the market, capable of printing models of significant size. (You'll get a chance to look more closely at the Rostock Max kit in Chapter 12.)
- » **3DR:** I designed an alternative Delta printer, which uses mainly 3D-printed parts for the structure of the machine (see Figure 10-6 in the previous chapter).

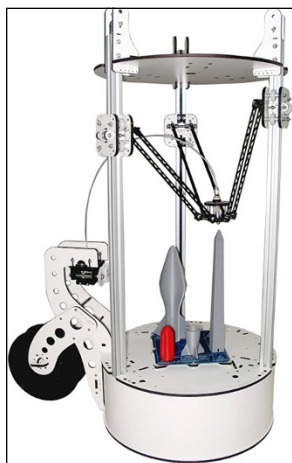


FIGURE 11-12:
A Rostock Max 3D
Delta printer,
designed by
SeeMeCNC.



TIP

Most RepRap printers can be scaled to different sizes, so don't assume that the stated build area of a machine is the maximum build area. Typically, a building envelope of 200 cubic millimeters is standard, but RepRap machines can be scaled up many times this size. Non-RepRap printers are usually limited by the size of the laser-cut frame, which isn't so easy for the individual builder to scale.

Choosing Print Media

With most desktop 3D printers, you have a wide choice of materials you can use for the build process. There is an even wider range you can use in paste form if you use the appropriate style of material extruder system.

Thermoplastic

Desktop 3D printers mainly use thermoplastics as the materials of choice for manufacturing objects.



WARNING

It's possible to use almost all types of thermoplastics, but melt temperature and toxicity are critical factors in material choice. Make sure that your work area is set up with all necessary safety precautions. Use good ventilation for all 3D printing, especially in a home environment. Charcoal-filtered fans like those used with soldering stations are good additions.

This section lists some common types of thermoplastics. A 3D printer normally uses polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), or polyethylene terephthalate (PET), but developers are experimenting with many other interesting materials. Some of the materials are designed for a specific purpose or aspect, such as temperature, strength, flexibility, optical clarity, or impact resistance. Other materials are simply designed to look good when they're polished after printing.

When a thermoplastic is processed for use in a 3D printer, it's usually produced in a factory with specialized plastic extruding equipment and new material. The material, when extruded as a tightly controlled plastic wire (round in cross-section), is called *filament*. 3D-printing filament is commonly available in standard 1.75mm diameter and a much older standard of 2.85mm. Machines that use 1.75mm are recommended as this will allow you access to the widest range of materials. 3D-printing filament originated in the automotive plastic welding industry.



TECHNICAL
STUFF

In the early days of home 3D printing, standard spools of 3mm plastic welding wire were used. Today, plastic extrusion companies all over the world manufacture dedicated filament for the 3D-printing industry in two standard sizes of 1.75mm and 2.85mm with a tight tolerance (± 0.1 mm diameter), and true concentricity of the filament ensures high-quality printed parts.

Although many suppliers use new materials in their filaments, the use of recycled plastic, or *regrind*, is a fine goal for 3D printing. One day, you'll be able to recycle plastic milk cartons and packaging to use in 3D printers. Many projects have been started with the aim of producing a system that can manufacture filament at home. Presently, however, creating regrind is a slow and complicated process. At the time of this writing, it's still easier and less expensive to buy ready-made filament on the roll.

Other, less common thermoplastic materials include nylon and mineral-filled *LayBrick*, a plastic- and chalk-filled material useful for architectural models. Another option is *laywood* or *woodfill*, which is PLA blended with 40 percent wood fiber (which I cover in more detail in the composite section later in this chapter). Laywood or WoodFill can be painted, drilled, tapped, and sanded much the same way as woods such as Medium Density Fiberboard (MDF).

PLA/PHA plastic

PLA is one of the most common types of 3D-printing filament. PLA plastic is manufactured from cornstarch; during the process, the lactic acid is polymerized. The resulting thermoplastic has been used in industry for many years. PLA is used for candy wrappers, coffee-jar lids, and many other products.

PLA can be recycled and starts to break down when exposed to industrial composting facilities. Because PLA is a nonpetrochemical plastic (not formed from oil), it's regarded as an eco-friendly choice.

PLA has a low *glass transition temperature* of 60°C, which is the point at which the material starts to turn from a solid to a liquid. The glass transition point is also the temperature used by a 3D printer's heated bed to hold a model in a stable state while it's being printed. Matching the glass transition point of a material is often critical to keep the part securely attached to the build platform during a print and also to minimize the warping effect caused by accumulated layers of melted plastic. (Figure 11-13 demonstrates how even large objects can resist warping.)

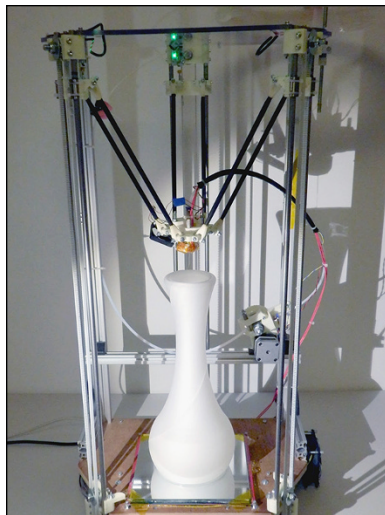


FIGURE 11-13: Large objects like this vase can be produced in PLA plastic without significant warping.

Another critical temperature to know in 3D printing is the *useful melting point* — when it's at a liquid state and can flow. For PLA, that temperature is around 160 ° C. A temperature between 160 and 210 ° C is often used for 3D printing with PLA. At a higher temperature, the plastic is too flexible for 3D printing and also starts to break down.

Fans are often used to cool the print layers during printing with PLA. This arrangement may sound like a bad idea, but for small prints being done very quickly, it's usually the only way to ensure that a layer is cool enough to allow the next layer to be added. Otherwise, you end up with a plastic blob rather than the object you had in mind. Also, using fans can minimize the curling of an object's printed edges, resulting in better overall surface quality.

Melting PLA produces a sweet smell something like cotton candy or popcorn, which makes it well suited to printing in a home environment. Polyhydroxyalkanoate (PHA) is similar to PLA but is made from fermented sugar rather than the cornstarch used in PLA. The formation of lactic acid isn't required, so the manufacturing process is more straightforward. PHA is starting to become more common, and you may also see blends of PLA+PHA.

PLA and PHA plastics in natural form are semitranslucent but can be altered with pigments into a wide range of translucent and opaque colors.



TIP

Some color pigments have various effects on the extrusion temperature and may prevent the object being printed from sticking to the 3D printer's build surface. It's a good idea to use uncolored natural or white material when you first use your 3D printer. Black materials can also be somewhat problematic for a few formulations as they tend to have a high level of carbon-black filler, affecting the flow characteristics of the material (which may force you to adjust the melting point temperature for printing).

A heated build platform isn't essential for using PLA. If you expect to do your print jobs at room temperature, you can use a cast acrylic platform or various types of tapes and adhesives to print smaller parts successfully. For objects measuring 130mm or more, however, a heated platform is recommended and is now almost always included as standard on even entry level machines.



WARNING

Some sources of materials used in low-cost 3D-printing filaments have been known to contain materials other than the plastic you were expecting. If this material is an additive or another type of thermoplastic, the resulting filament can be unpleasant or difficult to work with. If the other material can't be melted or won't pass through the extruder nozzle, it can jam your 3D printer. Be extra careful when using low-cost filaments, especially black material, because contaminants, rejected batches, other colors, and alternative materials can be hidden due to the dark color. Always buy from a high-quality branded source.

ABS

ABS is another common choice for 3D printing. Being oil-based, it's not eco-friendly like PLA, but it has the advantage of a much higher glass transition temperature. For parts and objects that are going to be subject to temperatures up to 100 ° C, ABS may be advantageous.

A heated build platform is essential for printing with ABS. A minimum temperature of 100 ° C is required for the platform, and a temperature around 240 ° C is required for the extruding nozzle.

Natural ABS is off-white but can be processed as clear or colored during manufacture via techniques similar to those used for PLA. ASA is similar to ABS and is now often more readily available as a filament for 3D printing.



TIP

Avoid fan cooling if you're working with ABS. A fan or even a breeze that cools ABS too quickly will make the plastic layers warp upward, knocking the printed object off the print bed before the process is finished. Result: an awful mess.



TECHNICAL
STUFF

Not all ABS is the same. The substance is manufactured from three chemicals, mixed in varying proportions to affect the properties of the finished plastic. Also, ABS from different suppliers can act very differently, requiring more or less heat to extrude or being harder, softer, or more brittle than other suppliers' products. ABS has much more variation than PLA does.

PET / PETG

PET is quickly becoming the go-to material for many 3D print users. It can be a very good alternative to ABS and PLA because it has similar impact resistance to ABS and higher temperature resistance than PLA. It usually has less odor during printing and warps significantly less than ABS. PET plastic is used for many types of plastic packaging, especially food and drink containers. PET can be produced in many different forms, but the most common types are PETT and PETG. For PET materials used by 3D printers, the generic term *polyester* is often used. Look for brand names such as nGen from ColorFabb, which uses Amphora co-polyester from Eastman. nGen filaments are specifically formulated for 3D printing.

Another popular PETT polyester is t-glase from Taulman3D. This material is designed specifically for 3D printing. Generic polyester filament is often based on PETG, a glycol modified polyester. Although this material is often great to use for large models for which PLA may be too brittle, it can exhibit more warping issues and even damage some glass build platform surfaces.

A heated build platform running at around 85°C is ideal for printing with polyester or co-polyester based materials. Fans can be used for cooling the extruded material in a similar way to cooling PLA.

Natural polyester is usually supplied as a clear filament but can be tinted or colored opaque during manufacture. PET bottles with the recycling symbol 1 can be ground and melted to produce recycled materials for 3D printing. As polyester is the world's third-most-produced polymer material, it causes significant environmental problems in places where many plastic tubs and bottles wash up from the sea. Several not-for-profit companies seek to recycle these waste plastic containers into 3D-printing filaments or other plastic products.



WARNING

Some polyester-based filaments crack, shatter, or even lift out sections of glass from a heated build platform. It's often recommended that you use a coating on the build platform to minimize damage. This coating can be a layer of generic poly-vinyl acrylic (PVA) glue-stick or a specifically formulated adhesive for 3D printing, such as Magigoo.

Composite or filled materials

You now also have a choice of more exotic 3D-printing materials, which often have a PLA or polyester base material and some solid fiber material (usually, less than 20 percent) mixed in. The most common composite material uses added wood particle fibers. The wood can be cherry, oak, bamboo, cork, or recovered waste wood. 3D models printed with wood filament are mostly plastic but create a wood effect and can be sanded, drilled, and even varnished.

The next-most-popular composite filament contains metal particles — anything from iron (which can be rusted after printing) to stainless steel and brass (which can be polished after printing to simulate solid shining metal). Copper, aluminum, bronze, and other metals are also available, often supplied on smaller rolls of filament; they cost significantly more than standard plastic filament does.

Metal filaments behave much like thermoplastic when printed. They may be much heavier and more expensive than plastic due to the metal content, but they're not as durable as real metal objects. Sanding and polishing of the surface need to be done by hand (or with a small rock tumbler) very carefully, so that the base plastic doesn't melt. After some significant manual effort, you can achieve great results with metal-filled materials. Unless you plan to polish, rust, or smooth the materials, however, using them may not be worth the extra cost if you're only looking for a metallic color.

Carbon fiber is another popular composite filament. The short carbon fibers add strength, resulting in a ridged matte finish on the printed part, but the object won't be nearly as strong as a traditional molded or layered carbon fiber object. Developers are experimenting with other filler materials and even with fragrances, such as coffee, pine, and strawberry.



REMEMBER

Filled materials may require a heated build platform. Ask the manufacturer what base material was used for the composite filament you're using. If the base material is PLA or PHA, a temperature of around 60 ° C is a good starting point. For polyester-based composites, start at around 85 ° C.

Most filled composite materials produce a slightly rough finish. Composite materials often can't reproduce fine features that a non-composite filament can achieve. Composite filaments also have a greater tendency to ooze or string during printing.

In recent years even foaming materials can now be 3D-printed. These expand as they are heated, forming a lightweight foam object, ideal for aircraft and drone models and cosplay armor or anywhere you need strength and a lightweight model.



TIP

Some composite materials are very expensive, so if you're printing with metal-filled filament that you intend to polish (such as BrassFill), consider printing with no bottom layers and a perimeter outline with low or no infill. After printing, you can fill the object with polyester resin or plaster of Paris to add weight and strength. When the plaster or resin hardens, it takes away any heat generated in the polishing process and limits damage caused by pressure applied to the thin walls of material. Because this hollow print method uses much less material than a solid print, you can print more objects at a lower cost per print. If you really need a metal-looking bottom, you can print that part later and glue it to the base of the object after filling.



WARNING

Almost all filled materials, including glow-in-the-dark materials, have an abrasive action on your 3D printer's nozzle. Carbon fiber filament can destroy a brass nozzle after printing just 500 grams. It's recommended that you use a specially hardened or stainless steel nozzle for many composite materials. Otherwise, be prepared to replace the nozzle after processing a few rolls of filled materials.

Paste

Paste materials can be used in 3D printers that have a modified extruder — usually, a syringe or other type of cylinder. Such extruders press out the paste material in much the same way that you press cake icing from a piping bag.

Syringes are often chosen for being food-safe, but don't reuse these syringes for different materials or try to use a normal thermoplastic extruder.

All sorts of food-based materials can be used in a 3D printer with an appropriate extruder, but the paste must have the consistency of toothpaste so that layers can be built up on top of one another. Frosting, marzipan, cookie-dough mix, and masa (Spanish dough used to make tortillas) are ideal candidates for 3D printing. Chocolate is a much more complex material for 3D printing, but you can print chocolate items at home. If you pay close attention to temperature and cooling methods, you can provide some wonderful possibilities for decoration and customize cakes and treats for loved ones and friends.

In addition to foods, almost any other material in paste form can be used as a 3D-printing material. Cements, fast-setting resins, ceramics, and even precious-metal clays can allow you to produce traditional artistic objects from solid materials (see Figure 11-14). (You can get a closer look at the paste extruder in Chapter 14.)



FIGURE 11-14: Fine porcelain clay can be printed with a paste extruder and then fired in a normal kiln to produce ceramic.

Identifying Key Components

Like the very early home computers, many early home 3D printers were available in kit form. Although assembling the parts is relatively straightforward, the build can be a little daunting unless you visualize how all the components come together to produce a working 3D printer.

Structural framework

The framework of a RepRap 3D printer is usually a material that's commonly available in many countries, which is one of the ways that RepRap makes 3D printing accessible to many people. Common threaded rods, such as M8 and M10 size, are often used as the framework. Some printer kits use laser-cut wooden or aluminum plates for the entire frame structure. Extruded aluminum tubes (often used for industrial racks or production equipment) can also provide a strong and lightweight framework for a 3D printer.

Extruders

The extruder and hot-end of a 3D printer are the most critical parts to ensure good quality and reliable printing. The last thing you want, after seven hours of an eight-hour print, is for the extruder drive to strip the filament or the hot-end nozzle to jam. These issues stop the flow of plastic and ruin your printed object. If you have too many of these problems, your new 3D printer will spend most of its time turned off or in a constant state of being fixed.

The most common style of hot-end has an aluminum heat sink and a brass nozzle with a small hole (typically, 0.4mm or 0.5mm). The small nozzle is where a stream of molten plastic is extruded onto your build platform layer after layer. Brass is often used, as it's easy to machine, wears well, and provides adequate heat conduction. Brass is also forgiving: If a separate screw-in nozzle end is brass, you're not likely to damage it. A stainless steel or high-temperature plastic section separates the heated nozzle from an aluminum heat sink, which is usually cooled to prevent the plastic filament from swelling and jamming before reaching the hot nozzle and melting into a controlled bead of molten plastic extrudate. Aluminum transfers heat quickly and can improve print speed, but aluminum hot-ends are rare.



TECHNICAL
STUFF

Although 0.5mm nozzle holes are common, smaller holes (down to around 0.15mm) allow for a finer level of detail. The smaller nozzle holes, however, increase print times dramatically — often up to 10 hours, even for small objects. On the other hand, a 0.6mm or 0.8mm nozzle hole size allows much faster print

times (usually with only a small loss of overall detail) for most types of 3D printing. You can retain a good level of vertical detail, even with a bigger nozzle hole, by printing lower layer heights. Models that are printed as a single outside wall, such as a cup or a pot, often benefit from a bigger nozzle that adds strength and wall thickness to the object.

The extruder nozzle can be screwed into a heating block or these two parts may be integrated and machined as one part. The heating block contains a heating element, which is usually a cartridge heater. A temperature sensor (usually, a thermistor) is also required to provide a closed-loop sensing system. The electronics can control the heating of the material being extruded to within a few degrees.

Another feature that every hot-end needs is a way to isolate the heating block from the incoming filament feed. This feature is fundamental, and if it's not carefully designed and accurately crafted, materials will jam. This section of the hot-end is called the thermal break. Commonly, the thermal break is made from a hollow stainless-steel tube or a high-temperature plastic such as PTFE (Teflon) and PEEK. PTFE has low friction against the incoming filament, which is important because as soon as the filament starts to reach its glass transition temperature, it acts more like rubber, gripping the walls of the cold-end. The cold-end holds the heating block in place and serves as an insulator, impeding the transfer of heat. Keeping the cold-end as cool as possible is critical. One common technique is to use a small fan to blow cool air against the cold-end and help maintain good thermal isolation between cold-end and hot-end.

Many types of RepRap hot-ends are available. Each type performs much the same job, but some designs are best suited to particular machines. The most common hot-ends include the following (see Figure 11-15):

- » **E3D:** This nozzle is designed for high-temperature materials and a very low degree of ooze, so it's excellent for accurate and fine printing.
- » **J-head:** This good all-around design is limited to temperatures below 250 °C because of the materials used. The J-head nozzle has more parts than the newer stainless-steel designs but is easy to use and service. Figure 11-16 shows assembled and exploded views of this nozzle.
- » **eMaker Bowden:** This hot-end is used in the small Huxley printer.
- » **Prusa V2:** This nozzle uses a stainless-steel barrel with aluminum cooling fins and can reach extremely high temperatures.
- » **Early RepRap hot-end design:** This hot-end is rarely used these days because its white PTFE thermal break often fails due to jamming or to operating at too high a temperature.

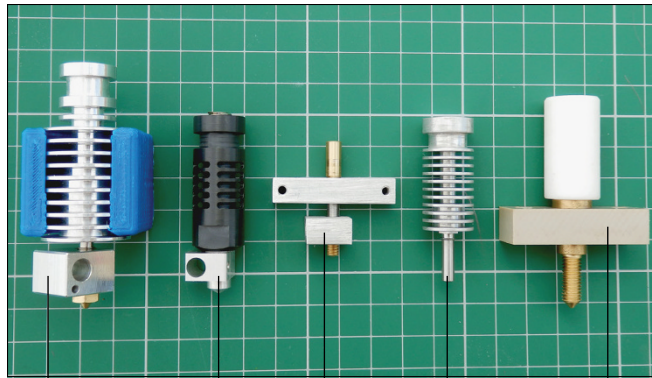


FIGURE 11-15: RepRap hot-ends.

E3D J-head eMaker
Bowden Prusa V2 Early design

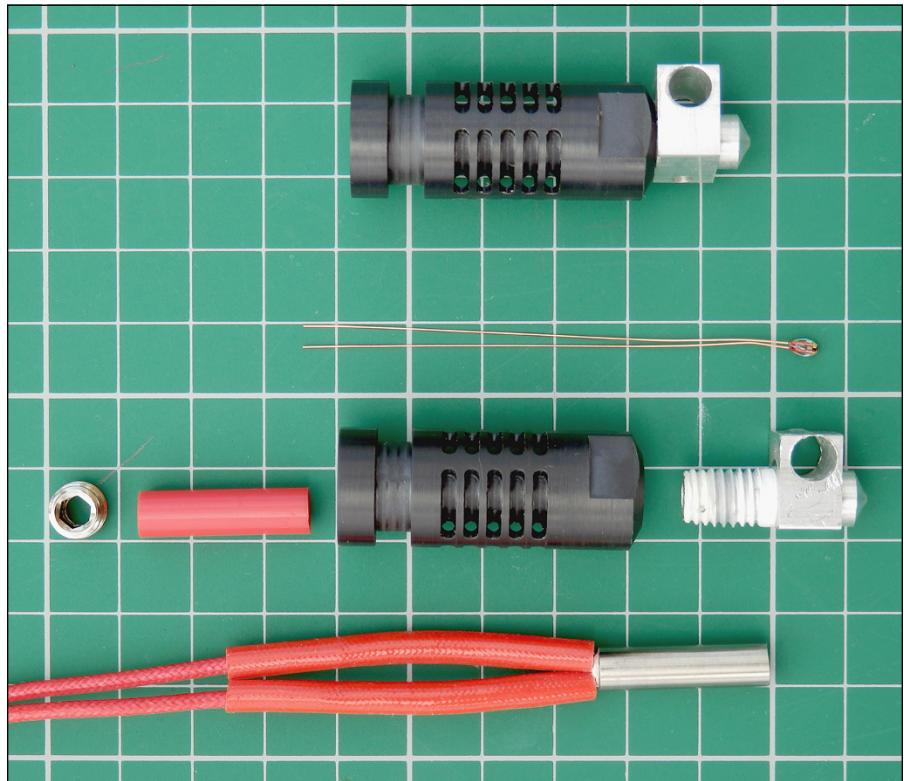


FIGURE 11-16: The J-head nozzle is now quite an old design, but it's still a great all-around choice.

Stainless steel is now the industry standard as the cold-end isolation material for hot-ends. Stainless steel can withstand much higher temperatures than PEEK and PTFE, so it can extrude thermoplastic materials with melting points higher than 250 ° C, such as polycarbonate (used in bulletproof glass). Even PEEK can be extruded, allowing you to print the cold-end insulator for another hot-end.

Advanced hot-end designs and interchangeable nozzle sizes (see Figure 11-17), including multiple nozzles and material mixing systems, are becoming more popular and reliable. The following designs will become common as more complex desktop 3D printers are developed:

» **E3D Cyclops:** This nozzle is designed to accept two separate material feeds and allow rapid switching between them. Because it has a single output nozzle, you need to be concerned about only one point of extrusion. The nozzle does have one small disadvantage: During switching from one material to the other, a small amount of mixing occurs. If you're using red plastic on one side and yellow on the other, for example, you see a section of orange as you switch from one to the other.

This problem is usually solved by using a material dump location (outside of the normal print area) so the nozzle can purge out (clean) a material or color so that another color or different material is not contaminated by the previous one used. Another method is to use a prime pillar that produces a useless mixed color or material pillar by printing out the remaining mixed material until the new material flow is clean or has fully changed color.

One further limitation of this nozzle is that both materials need to have compatible temperatures to function together in a single heating system. You couldn't, for example, use PLA on one side and ABS on the other.

» **E3D Chimera:** This dual-nozzle and dual-heating system allows for a wider choice of dissimilar materials, which can have different temperatures and extrusion profiles. You can also use two different sizes of nozzles, which can be useful if you want to speed the infill by using a large nozzle hole while keeping the outline high-quality by using a smaller nozzle. The main disadvantage of a dual-nozzle system is that you need to carefully calibrate and align the two nozzles so that the extrusions line up. Also, the inactive nozzle may ooze plastic or accidentally knock into a previously printed feature, causing misalignment.

» **E3D Volcano:** The Volcano hot-end allows a high deposition rate of plastic flow so that parts can be built quickly, often with an increased nozzle size (around 0.6mm to 1.2mm, compared with the standard 0.4mm). The main drawback of the Volcano is a tendency to ooze plastic, as you have a reservoir

of ready-melted plastic at any time. This drawback can be balanced by faster printing and increased extruder retraction. This design is excellent for printing large parts in which fine details aren't critical and print time is important.

- » **E3D Hemera:** The Hemera kit is a combined extruder feeder, cold-end-and-hot-end all-in-one, all metal, extrusion system. It still uses the industry standard V6 nozzles and has a high performance of thermal melt capabilities, making it suitable for upgrading many lower quality desktop 3D printers. (See Figure 11-18.)

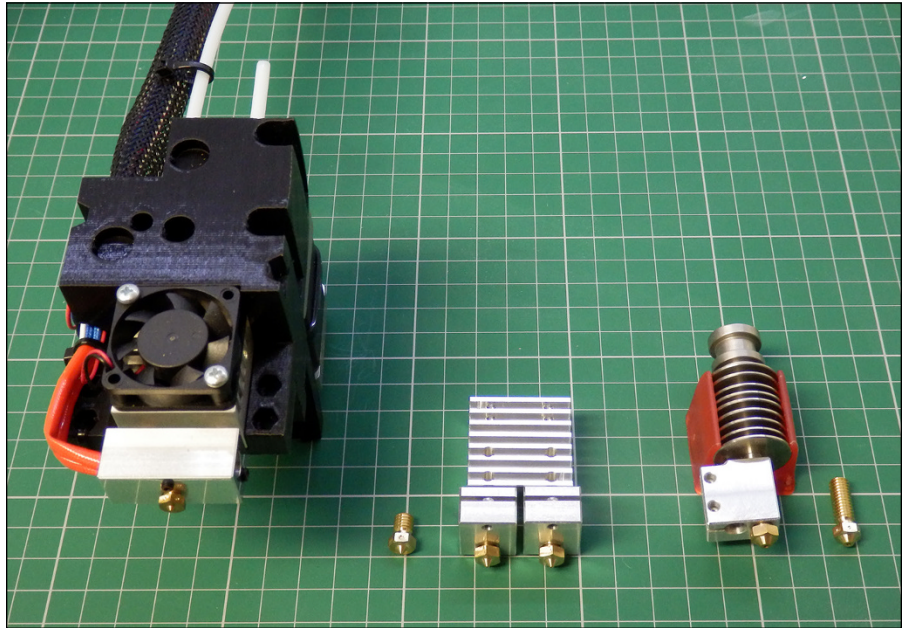


FIGURE 11-17: Specialist and multiple-nozzle RepRap hot-ends: Cyclops (left), Chimera (middle), and Volcano (right).

Hot-end and nozzle design is a lively area of 3D-printer development, from tiny-geometry nozzle apertures to specialist materials that reduce wear and improve performance. It is a significant design trend well worth keeping tabs on.

The most common type of nozzle is the E3D V6, which has a standard range of nozzles in brass, hardened steel, and stainless steel to choose from. Starting at 0.15mm and going up to 1.2mm, these industry standard nozzles are now common in most types of desktop 3D printers. (See Figure 11-19.)

Alternative V6 design nozzles are also available. Some focus on being higher flow or even come with a ruby for the nozzle face to help reduce the wear on the nozzle aperture.



FIGURE 11-18:
The E3D Hemera
all metal
extrusion system
with integrated
cold block and
hot-end nozzle.



FIGURE 11-19:
A range of V6
nozzles in
different
diameters from
0.2mm to 1.0mm
and in brass,
stainless steel,
and hardened
steel.

Build plates

The build plate of your 3D printer can be made from various materials. Because many 3D printers move the build plate backward and forward on the Y axis, it's desirable to make the build plate and any heating elements as lightweight as possible so that the Y axis can move and accelerate quickly.

The build plate is normally a flat surface of sprung steel, glass, or aluminum, often with a printed circuit board (PCB) underneath. The PCB acts as a heating element when powered by the 3D printer's electronics. Also required are thermal insulation and a way to level the build plate mechanically. With a heated build plate, you can print with a wider range of materials, but heating the build plate adds a level of complexity to the printing process and the electronics require a much more powerful power supply.



REMEMBER

Many 3D printers allow you to print PLA without a heated build surface. This lower temperature keeps down the overall cost and power requirements of a 3D printer but limits you to printing with a smaller range of materials. You can almost always add a heated bed later if you find that your project requires one.

Instead of printing objects directly to the heating PCB, you need to have a smooth surface to print to, such as a sheet of glass. PLA, for example, sticks to clean glass when heated to 60 ° C and pops off the glass when it cools.

If you're not using a heated surface with PLA, one of the best materials to use is 3M Blue Painter's Tape for Multi-Surfaces (part number 2090). Covering the printing area with this tape allows many prints to be completed before you have to cover the build plate with new tape. The surface finish of the side touching the tape takes on the mottled appearance of the tape, however.



REMEMBER

A plain cast-acrylic build surface can also be used for PLA but be very careful that you fully calibrate the hot-end nozzle's distance from the acrylic. If the nozzle is too close, the printed object will be almost impossible to remove from the surface after printing.

ABS has the opposite problem: It can have trouble sticking to the build plate. For successful ABS printing, heat the surface to 100 ° C. In addition, you have to add a layer (usually, Kapton or PET tape) to the heated glass plate to control how the ABS object sticks to the build plate. If you still have problems getting your ABS parts to stick, painting a thinned solution of ABS and acetone on the extra layer (glass, Kapton, or PET) adds bonding strength.

Finding good materials for the print surface is an ongoing quest in home 3D printing. So far, the best material for a 3D printer's build platform is a sheet of PEI (polyethylenimine) stuck to high-temperature borosilicate glass or the PCB heater plate. This build platform is the costliest type and must be replaced after several hundred models have been printed. No other single surface has been found to be suitable for all thermoplastic filaments. Thus, as a lower-cost alternative, many users opt to fix the glass plate to the PCB heater plate with office binder clips. This method allows quick removal of build-plate surfaces and exchange with other materials if necessary.



TIP

Printing with nylon requires the use of a cellulose-based printing surface. Tufnol (a solid laminated sheet of resin and cloth), wood, or cardboard is often used successfully.

Control interface electronics

The electronics of your 3D printer are likely to be based on the open-source Arduino platform or a common ARM 32-bit device like the STM32. Rapid advances in low-cost control electronics have started to filter into use with 3D printers, including the use of color displays, 32-bit processors, wireless control and connection to networks, and web-based control and monitoring of print jobs. (I discuss various RepRap electronics, including their modular parts and connections, in greater detail in Chapter 13.)



REMEMBER

The embedded program running on the electronics control board for a 3D printer is called the *firmware*. It's quite normal for you to be required to change key settings in this firmware, either from the onboard display or as a configuration file to upload these changes to the electronics.

Software

Another critical part of 3D printing is the software used to design, output (or convert), repair, and then process 3D models into code that the printer understands.

In Chapter 15, I give an overview of the software required for producing 3D objects and explore the software used to process and manipulate 3D models for your RepRap 3D printer. In the following sections, however, I highlight a few basic 3D-printing applications.

Slic3r and its successors Prusaslicer & Super Slic3r

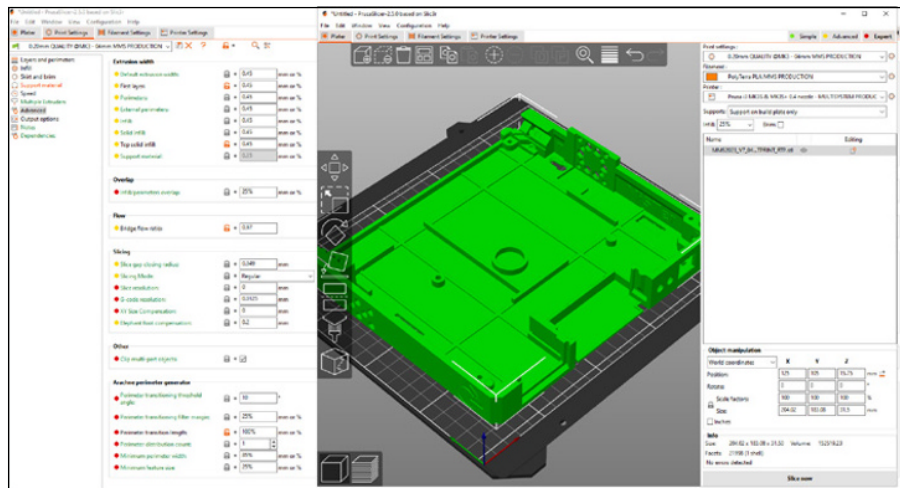
Slic3r (see Figure 11-20), designed by Alessandro Ranellucci, is an open-source conversion tool for 3D model processing for printing. The Slic3r software is available for Windows, Mac, and Linux at <http://slic3r.org>. This tool formed the basis of many slicing engines available today; in fact, most 3D-printing companies have a custom version of Slic3r. (See Figure 11-21 for an example.) The capabilities are upgraded regularly, which makes it a good choice for the rapid developments in 3D printing. Check the website often to find out what's new or improved.

The main task of any 3D print-slicing program is to slice (process) a 3D model into fine layers and plan paths for the extruder to travel as it deposits the material used on each layer. When the print-slicing program does its job correctly, the 3D printer's firmware processes this data and controls the movement of the printer's components to print the finished model.



FIGURE 11-20:
The open-source Slic3r project homepage.

FIGURE 11-21:
The open-source Prusaslicer is based on the original Slic3r project. Many settings are available for tuning every aspect of your model processing into Gcode.



The slicing program also analyzes the model for printability and then determines whether additional commands are needed — whether to print extra material to help support a bridge, for example. Further, if you elect to use support material, the slicer does its best to add the required breakaway support material automatically, so that you don't have to change the original model. Thus, a slicing program must apply some intelligence to processing a model for 3D printing. Any overhangs of material, features, and holes that make plastic span sections of bridging may require alterations to the path of the nozzle. This can be done by changing the perimeter outlines of the object or detecting when solid layers that go in a specific direction must bridge a gap (span across back and forth) in an object to keep the print strong and appealing in its final appearance.

Cura

Cura (see Figure 11-22) is another option for processing and slicing 3D models. Cura is an open-source program developed and maintained by Ultimaker in its early days and by David Bramm, along with many members of the 3D-printing community. Custom versions of Cura are included with many 3D printers as a starting point for model processing. Like Simplify3D and Slic3r, Cura can store profiles of machines, materials, and common print configurations to make choosing easier (For more on Cura, check out <https://github.com/Ultimaker/Cura>.)

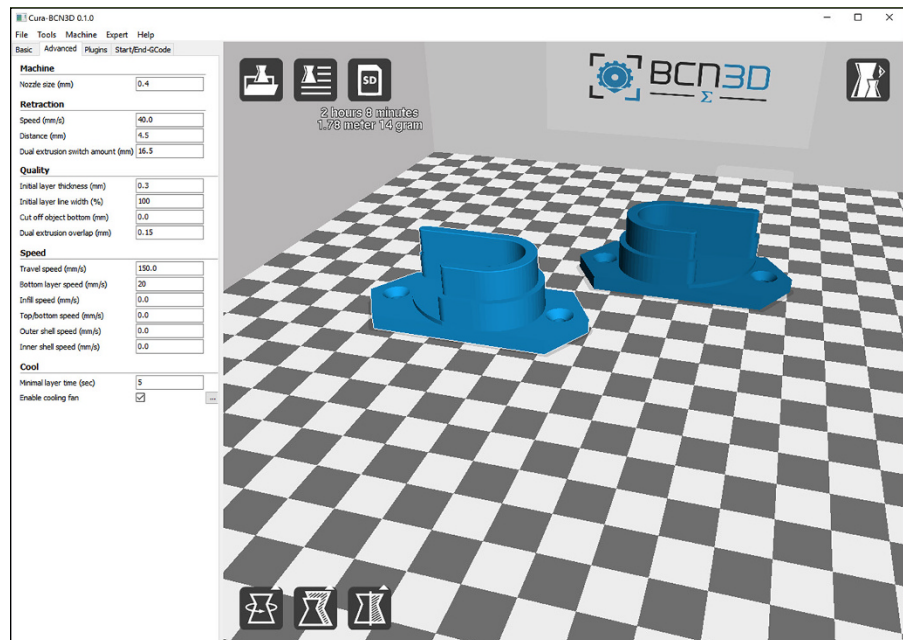


FIGURE 11-22:
Cura slicing
software.



RepRap 3D printers use a control language called *G code*, as do commercial 3D printers that cost upward of \$50,000. G code is an industry-standard set of commands and codes used to script the path that a 3D printer (or even a CNC milling machine) uses to produce a 3D object. Thus, all the software tools used for RepRap can also be used for high-end machines. The difference with RepRap is that the further development of G code is highly dynamic; new codes and commands can be added to the G code set as the technology develops. Many slicing programs exist for 3D printing, but Slic3r is a favorite among RepRap users all over the world. Other slicing programs that you may want to investigate include Repetier host and Kisslicer.

Netfabb

Netfabb is a powerful commercial software package for many aspects of 3D file manipulation. It's not open-source, but it has a number of older versions that are basic but still amazingly functional. You may need to search around for older free versions when Netfabb was a stand-alone company. It's now owned by Autodesk and is available to buy as a professional package.

RepRap users favor Netfabb Basic for checking model files before sending them to the slicing program. Netfabb allows you to rotate, scale, and modify (or fix) your object models. Loading a model into Netfabb before loading it into Slic3r enables you to ensure that the model looks 3D-printable, that it's in the correct orientation, and that it prints at the size you expect and require.

Netfabb Basic is available for Windows, Mac, and Linux. A cloud-based version is available and is often even better at fixing issues with 3D model meshes that contain errors or refuse to slice correctly.

Professional versions along with specific packages of Netfabb tailored to certain 3D printers are available for purchase.

Pronterface & Printron

Pronterface is an open-source RepRap user interface for controlling your 3D printer and sending Gcode files off to print. The complete Printron package of software was developed by Kliment Yanev and is widely used in the RepRap home 3D-printing community.

The Printron package is available for Windows, Mac, and Linux at <http://koti.kapsi.fi/~kliment/printron>.

Pronterface is an essential program for easy use of your 3D printer. In Chapter 15, I show you how to use Pronterface to control, set up, and calibrate a 3D printer, so it's well worth downloading in preparation.



TIP

Pronterface is a user interface for control of your 3D printer. You can link Slic3r into Pronterface, which allows you to load models, slice them, and immediately transfer the data to your 3D printer and start a print sequence.

Repetier-Host

Repetier-Host is a free alternative to Pronterface that provides a control panel for your 3D printer. It can also be linked to Slic3r.

Repetier-Host is available for Windows, Mac, and Linux, and can be downloaded at <https://www.repetier.com/downloads>.

ReplicatorG

Admittedly, ReplicatorG is now quite old, but it is still a well-established open-source package for both model slicing and 3D printer control. It's widely used by some closed-source manufacturers of 3D printers but did not attain wide popularity among RepRap users and developers.

ReplicatorG is available for Windows, Mac, and Linux at <http://replicat.org>.

5 Understanding and Using Your 3D Printer

IN THIS PART . . .

Select your own 3D printer from a part assembled kit or a ready-to-use built machine.

Service, configure, and calibrate your 3D printer to keep it performing in peak condition.

Find out how to print in multiple colors.

Select design and printing software.

Learn to design for the 3D-printing process.

Take your first steps toward creating your own practical 3D-printed object.

IN THIS CHAPTER

- » Sourcing a kit 3D printer
- » Obtaining printed parts or spares for machine assembly
- » Looking at frame structure and configuration options
- » Assembling the moving axis
- » Connecting sensors, displays, and cables

Chapter **12**

Assembling Kits and Reviewing Machine Setup

This chapter describes many of the component parts of a 3D printer. We look at 3D-printer kits using both individual components and as semi-built modular assemblies for you to assemble. I'll describe how the machine motion and sensing operations work and prepare you for wiring and incorporating the electronics I discuss in Chapter 13.

Although this chapter covers a lot of ground, you shouldn't think of it as a full-build guide for a specific printer. Instead, it's meant to further assist you in deciding whether a complete kit, modular kit, or a fully assembled 3D printer is the most suitable path to take when sourcing a machine for your needs.

Sourcing a Kit 3D Printer

No one would deny that certain benefits come from buying a 3D printer as a kit; the price is often lower, and shipping costs also can be lower as they often come in a smaller package. And yet, it's not only cost savings that make a kit or modular system appealing. Many 3D printers that come as a kit are based on RepRap or other open-source designs or take the same open-source approach by using more standardized parts and less custom components. This can be quite useful when parts need replacing, or if a future upgrade is available later on in the life of the machine.

As I discuss earlier in this book, assembling or constructing your own 3D printer is well worth the effort. Buying one that's already assembled may sound like a good idea, but in reality, putting it together yourself will help you better understand how the machine works so you can keep it up and running over the long term. Believe me, you are going to have to replace parts and do regular maintenance over the life of the machine, and knowing how the pieces are put together will be an enormous help with these tasks. Even the relatively easy tasks, such as clearing clogs in the print head and extruder system, are a lot easier if you have a solid overview of your machine's mechanics.

Working with kits

Going with a kit of ready-to-use parts can be one of the best ways to start your open-source 3D printing journey if you are the sort of person who enjoys building up a system from a number of parts or even raw components. A good kit will have all the parts you require, cut to size and ready to assemble. A poor kit will have unlabeled and unnumbered parts all mixed together, with no instructions or guidance about what to do next. When it comes to good open-source/RepRap kits, all of them should include labeled bags of individual parts or fixings, while a really great kit (see Figure 12-1) will also include the tools you need to assemble the machine — usually, open-end wrenches or Allen keys. This kit is also likely to include a link to online instructions or to a fully detailed manual or section of a forum or wiki where you can find out more about your kit and its assembly.



REMEMBER

A number of 3D-printing manufacturers — Prusa Printers, to name just one — supply kit versions of their 3D printers as well as fully assembled options if you prefer.

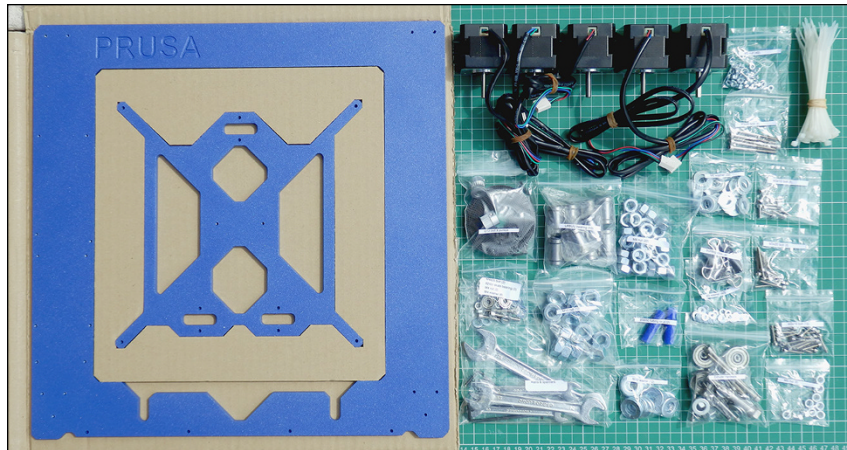


FIGURE 12-1:
An impressive
3D-printing kit.

Open-source and community-designed machines are also still popular, but they may not be ideal for your first 3D printer. One example here would be the Voron 3D printer, which is most often bought as a complete build kit of parts. It's a very capable machine but can be a challenge to build, test, and calibrate if you don't have all that much experience with using 3D printers. That said, the community forums and detailed assembly manual are being refined all the time to make it easier for new users to get started with assembly and use. To discover more about the Voron, check out <https://www.vorondesign.com/> and <https://docs.vorondesign.com/build/mechanical/>.



REMEMBER

Some of the most adventurous new desktop 3D printers may only be available as a self-sourced kit. With such kits, the designs tend to be frequently updated to take advantage of advances in the field, putting them in a position to push boundaries when it comes to the capabilities of these machines. It's an exciting hobby to follow and be part of.



WARNING

In recent years, some vendors have struggled to sell high-quality kits due to an increase in low-cost (and sometimes extremely low-quality) ready-assembled machines. As the saying goes, if it looks too good to be true, it probably is. Just be aware that you can often find 3D-printer kits and fully assembled machines for less than \$100. A few of these kits and machines may be acceptable, and others may be a great value for spare parts, but just as often these kits or machines end up sitting in the box or can't operate for any significant period without developing a problem.

Whether you decide on a kit or a ready-assembled 3D printer, try not to go for the lowest-cost design or an unknown design for your first machine. Making a terrible kit work well can be quite fun, but only when you are confident about the assembly, setup, and calibration process.

Know before you go

Kits can vary greatly in quality. Before you buy, know what to look for from kit suppliers and ask questions if the vendors don't provide the information you need. Some of the questions you might ask include the following:



REMEMBER

- » **What materials were used to produce the 3D-printed parts and what is the fill density of those parts?** It's good to know the material you're relying on. Some kit suppliers provide some parts made of acrylonitrile butadiene styrene (ABS) if they require a higher temperature on the machine than polylactic acid (PLA) parts do. In almost all cases, there's nothing wrong with using PLA for the machine construction. In fact, if the 3D printer design you've selected uses 3D-printed gears to drive the extruder or the motion of the machine, these gears *should* be made of PLA; they'll have a much longer wear life than gears made of ABS would.

Look for suppliers that take pains to offer the correct materials for the printer you selected. You're looking for a minimum of 25 percent plastic infill inside the 3D-printed components for strong parts. 3D-printed extruder components should be printed with at least 35 percent infill. Ask the vendor to send you an image of the actual printed parts before you buy, if possible. Some community members have also recently started printing sets of 3D-printed parts for free or at a low fee to cover postage costs, on the understanding that when you have the machine fully working, you also then print out a set and donate to another community member who's interested in building up a new machine or prototype design.

- » **What electronics are being provided and are they RepRap standards or custom developments?** Electronics may not be provided in the kit; it's quite common to have to buy electronics separately from the mechanical kit.
- » **Is the kit based on a recent release of the 3D printer you're considering?**
- » **If the kit has laser-cut parts, what material is used, and how thick is it?** Check with other sources and suppliers to see whether they're cutting corners by using thinner or flimsier materials.
- » **Are the linear rails provided in the kit stainless steel or basic carbon steel?** Paying a little more for stainless steel is well worthwhile. Parts made of stainless steel wear better than parts made of carbon steel, and they don't tend to produce as much black-oil residue on the rods and bearings.
- » **What motors are provided with the kit?** Make sure that the motors are true bipolar four-wire motors and ask what their current rating is. Also ask whether the motors have cables with connectors already fitted onto the ends.



REMEMBER

NEMA 17 motors are commonly used in RepRap kits; these motors have a stated current rating depending on the overall length of their body. You're looking for a minimum of 1.2 amperes (A). A more powerful motor will be rated at 1.7 A; the maximum rating for a NEMA 17 motor is around 2.5 A.

- » **Are plastic parts included?** Some kit suppliers may not provide the 3D-printed plastic parts; check to see whether plastic parts are a separate option. You may be expected to print your own.

Obtaining Printed Parts for Machine Assembly

Self-sourcing all the parts — that is, finding what you need on your own — can be good when you want to build more than one 3D printer or when a group of users plans to build the same printer. Often, if you try to buy parts for just one printer, the parts will cost you as much as (or even more than) a ready-made kit, which is why a good kit supplier provides you all the information you need to buy or identify all the parts required for the open-source/RepRap printer you're interested in, since the information is already online anyway. Taking the trouble, time, and extra risk to source all the parts yourself can save significant cost when you're building with a group of friends or at a local hackerspace or fab-lab.



REMEMBER

If you're building one printer and decide to self-source, you may need to buy more components than you really require or pay significantly more for the small number you need. Also, you may end up paying significant delivery and duty fees to get hold of all the parts you need from around the world. Finally, be aware that it's not uncommon to find poor-quality components or substitute parts that you weren't expecting or that don't fit your machine. For this reason, it's often better to buy a complete kit from a single supplier than to self-source.



TIP

If this printer is your first 3D printer or if you don't like the idea of spending a lot of time ordering parts from many suppliers, a kit is the best way to start.

Printing your own

When you have a working 3D printer, the job of making another one for yourself or a friend is almost totally under your control. Even upgrades and spare parts for your own 3D printer are straightforward to print.

Many open-source and RepRap printers are becoming self-reliant and more printable all the time. The unique self-replicating nature of RepRap technology means that you can modify, upgrade, and repair machines yourself, without relying on overpriced spare parts.



REMEMBER

You can use professional 3D-printing services and online print shops to get a set of 3D printer machine parts if you want, but that option costs a lot more than using another desktop machine to produce the parts for you.

Asking the community

It's becoming more commonplace to find someone with a 3D printer nearby. Many such people are willing to print a set of parts for a reasonable cost or to trade for other materials or services. One way to justify the cost of owning a desktop 3D printer is the capability to print a few good sets of parts to sell or trade for less money than buying them from a professional 3D-printing service. Companies such as 3DHubs (<https://www.hubs.com/>) help link people who need any sort of 3D-printed parts with individuals and professional companies that can offer to produce one part or as many parts as required. It's often a one-to-one service, so you get to know and trust each other. One nice side effect is that it does not take long before you begin to learn what materials and settings work for different types of models.

Understanding the Machine Motion

After you obtain the parts for your open-source/desktop 3D printer (or even before), and before you put the printer together, consider how the finished device is supposed to work. The components you can use for machine motion cover a wide range of materials, dimensions, and specifications. In this section, I'll have you look at some common and experimental ways to achieve the linear movement that makes 3D printing happen.

Z-axis motion

The vertical axis, called the *Z axis* on a Cartesian machine, is normally driven slowly and with a high-resolution setting to achieve fine detail and precisely printed layers.

Many machines are forced to lift the entire moving X carriage, including the extruder with motor and hot-end, to achieve vertical Z-axis movement. Often, these machines use two stepper motors (highly accurate positioning motors, discussed in detail during Chapter 13) — one on each side of the machine. Both motors run from one stepper-motor output and must stay in sync.

On many desktop 3D printers, a vertical Z carriage achieves this lift through a pair of simple threaded rods attached to the motor shaft of two stepper motors. A normal nut is trapped in the 3D-printed Z carriage so that when the motor rotates, the nut is driven up and down the threaded rod. Do this on both sides of the machine, and you achieve parallel lift. This arrangement automatically provides fine resolution for your print layers because one complete rotation, even for coarse M8 rods, moves the carriage only 1.25mm up or down per rotation. This technique is a simple, low-cost way to achieve fine resolution of movement. The main drawback is that a standard nut and standard threaded rod aren't optimized for all the motion that 3D printing requires. You have to carefully limit the speed at which you drive the motors; otherwise, they'll stall or skip.

Fortunately, a slow vertical Z axis isn't a major limiting factor for most types of 3D printing. The print head spends a lot more time moving on the X and Y axes to print each layer than it does moving vertically. This type of threaded-rod movement isn't used for the X and Y axes of a 3D printer, however, because the motion would be unacceptably slow.



TIP

It can be a good thing to enable a Z lift feature that makes the extruder carriage jump up every time the machine has to move to a new printing point. With this feature, you can stop the print nozzle from catching on a piece of already-printed plastic, which can knock the model out of alignment. You want to make your printer do a Z lift as quickly as your Z axis allows.

Many original RepRap/open-source machines used M8 (8mm) or equivalent imperial-size threaded rods for the Z axis. More common today are M6 or M5 rods, which provide finer layers and can still be driven precisely enough for high-quality results. The printer shown in Figure 12-2 uses an M5 threaded rod and a trapped M5 nut, and the connection to the motor is made with a short section of vinyl tube to allow threaded-rod rotary motion. A solid connection to the motor — one with no allowance for rotary motion — can cause the threaded rod to fight with the smooth vertical rods, which can cause print layers to be out of alignment.

Other products are specifically designed for this sort of linear movement; they can turn much more quickly than the standard threaded-rod-based systems do. They cost more, however, and can be harder to source and mount in your 3D printer.

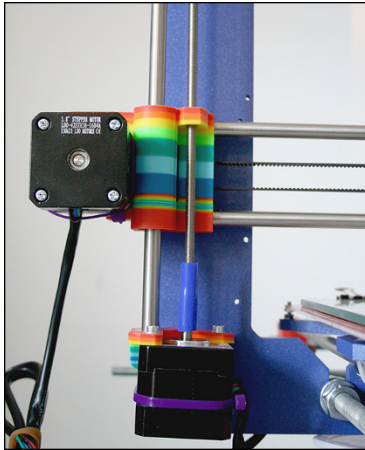


FIGURE 12-2:
The vertical Z-axis drive on a Prusa i3 printer uses an M5 threaded rod and a trapped M5 nut.

Figure 12-3 shows three movement systems that you could use for the vertical Z axis. On the left are an M8 threaded rod, an M8 nut, and a typical printer carriage to hold the nut. In the middle is a generic unbranded lead screw that's machined for linear movement and a matching square nut, which has to be housed in a 3D-printer carriage. On the right is a fully machined ball screw, which can achieve high-speed motion via a spiral of trapped ball bearings and could be used for other axis movement if desired. This system is significantly more expensive than the other two shown in the figure.

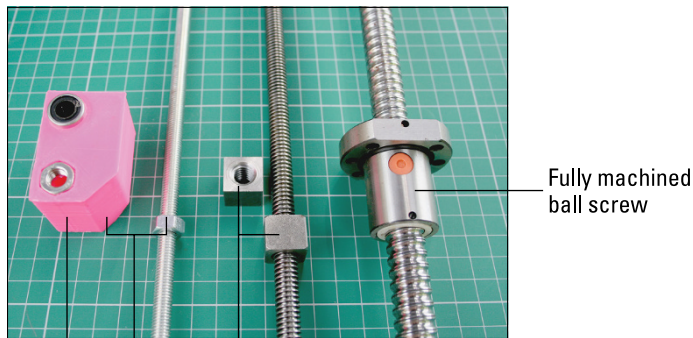


FIGURE 12-3:
Three vertical Z-axis movement systems.

Printer carriage

ACME lead screw and square nut
M8 threaded rod and M8 threaded nut

Fully machined ball screw

X and Y motion

The X and Y motion of a 3D printer has to be as fast as possible; the faster you can position the print head at various points around the build plate, the faster you can

produce 3D models. For this reason, we commonly use precision timing belts and cogged pulleys connected directly to the motor shaft to carry out these particular movements.

As with the Z axis, you require a good level of resolution for these movements. The belts we normally use are 5mm or 2.5mm tooth pitch; more recently, a 2mm version has become very popular. These timing belts have fine steel wires that stop the belt from stretching; belts just wear out over time but should offer a few good years of printing.

Less common are line-based drive systems, which use high-strength braided fishing line wrapped around a printed spool attached to the motor shaft. The use of fishing line, once popular on Delta-based printers, can have several benefits, including reduced noise and increased speed, and the line can usually be tightened to a greater degree than timing belts can. Fishing line also costs a lot less than timing belts do. These types of line drive systems are not so common on desktop 3D printers in recent years. The Hangprinter (see Chapter 10 for further details) is a nice example of spectra fishing line being used to form the main A, B, & C Delta axis of a very large-scale machine designed to 3D-print practical full-sized chairs, desks or large sculptures and artistic 3D objects.

Figure 12-4 shows a few drive systems used for X and Y movement. On the left is a printed spool with wraps of high-tensile braided fishing line, which is a low-cost system that can achieve smooth, fast motion. The black GT 2.2mm timing belt in the middle is a popular choice for many 3D-printer designs and kits. At the back are the 2.5mm pitch white belts that are commonly used in Europe, along with matching aluminum pulleys.

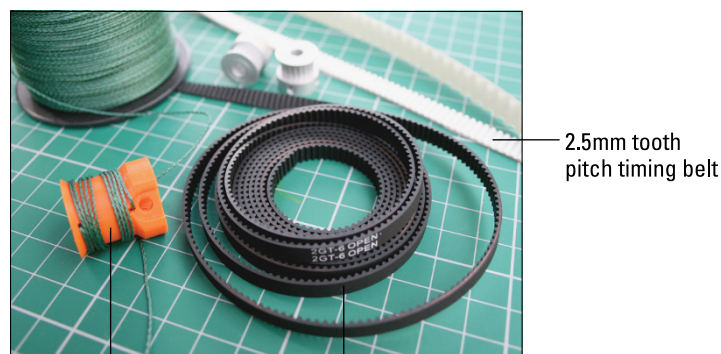


FIGURE 12-4:
A selection of
drive systems
used for X and Y
movement.

Printed spool
wrapped with
fishing line

GT-2.2mm tooth
pitch timing belt

2.5mm tooth
pitch timing belt

Another important part of the movement system is the rails that the X, Y, or Z carriages travel. These smooth rods (or drill rods) are most often 8mm or 6mm in diameter, but depending on the size of the machine, 10mm or bigger rods may be required. These rails are most often mounted alongside the threaded rod or timing belt. The carriage slides along these rods via either bearings or bushings, which can be printed or made from brass.

Linear bearings are professionally made, with a ring of small ball bearings inside a metal body; these bearings slide against the rod and provide smooth motion. Although these bearings offer long life, they generate noise as they slide along. If a lower-noise solution is preferable, brass or 3D-printed bushings are ideal. Although bushings wear out much more quickly than linear bearings do, replacement bushings can be printed for very little cost.

Figure 12-5 depicts rods and bearings for 3D printing. On the left is an 8mm stainless-steel smooth rod used in a Z-axis assembly: A linear bearing fits into the 3D-printed Z carriage and slides up and down the rod. On the right, a 6mm steel rod and 3D-printed PLA bushing provide a low-cost, perfectly acceptable alternative.



FIGURE 12-5:
The rods and bearings used in a 3D printer allow the carriage or axis to slide smoothly along or up and down.

8mm stainless-steel smooth rod and bearing

6mm steel rod with a 3D-printed PLA bushing

The movement system for Delta-based 3D printers is the same as the X or Y axis of a Cartesian system, but all three axes X (A), Y (B), and Z (C) are identical and travel vertically at three points of a triangle. The Delta system requires long lengths of belt or fishing line. Along with the reduction in noise, fishing line costs considerably less than belts do and takes up less space.

Building the Printer Frame

Although the frame of a desktop 3D printer can vary among designs and generations, all frames perform the same function: to provide a strong, level, accurate structure to which to attach all the other parts of the 3D printer. The following list describes four common RepRap designs to provide some history about the development of desktop 3D printers:

» **Threaded-rod frames (Prusa i3 printers):** RepRap 3D printers started by using threaded rods for the frame assembly, which allowed accurate configuration with the strength and simplicity of 3D-printed parts

The bottom frame of a Prusa i3 printer is constructed of M8 and M10 threaded rods (see Figure 12-6). These rods can be spaced and adjusted to create a strong structure. In between the rods is the Y idler timing belt mount, on which a bearing is mounted and around which the belt is threaded. At each side on top of the 3D-printed corner sections, a pair of parallel, smooth 8mm stainless steel rods form the Y axis of the 3D printer motion system.

The Prusa i3 also uses two laser-cut parts: the Y-axis plate that moves forward and backward (see Figure 12-7), and the frame, which needs to be accurately spaced for the movement to slide freely. Fortunately, threaded-rod construction is easy to adjust for perfect spacing.

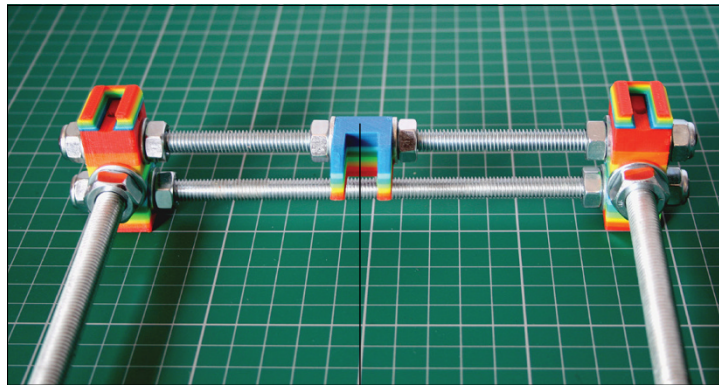


FIGURE 12-6:
The bottom
frame of a Prusa
i3 printer.

Y idler timing belt mount

Figure 12-8 shows the finished Y-axis assembly, which includes the motor, a GT2 timing belt, and an idler pulley. One side of the belt is fixed to the laser-cut Y-axis plate; 8mm smooth rods are fixed on the ends of the threaded-rod frame to allow movement.

FIGURE 12-7: The Y-axis plate, made of 6mm-thick aluminum, requires 3 LM8UU linear bearings zip-tied on and a 3D-printed Y belt clamp bolted in place.

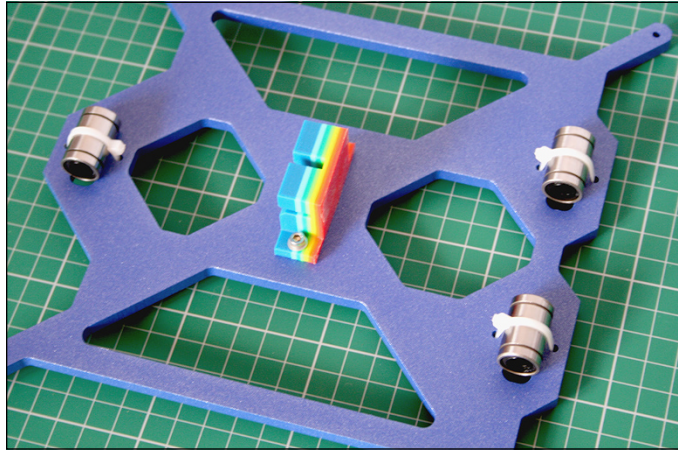
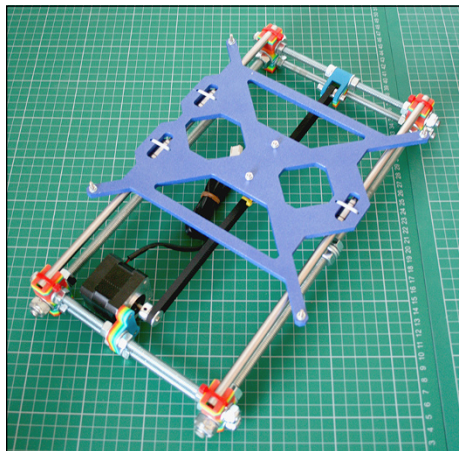


FIGURE 12-8: The finished Y-axis assembly.



» **Laser-cut and aluminum frames (MendelMax Version 2 printers):** The MendelMax V2 design uses many laser-cut aluminum plates and standard 20mm extruded aluminum lengths to build the main structure of the 3D printer. (See Figure 12-9.)

Bolts and trapped nuts are used to build the frame. Careful measuring and alignment are required. This assembly produces a very heavy but solid frame.

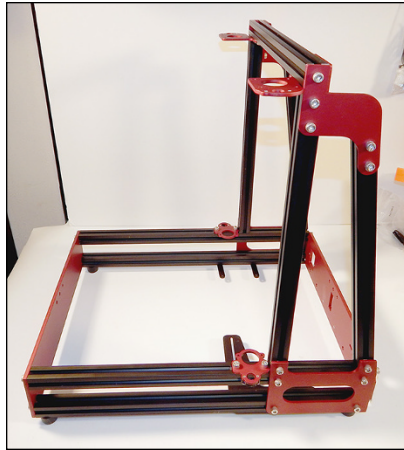


FIGURE 12-9:
A MendelMax V2
frame.

» **Laser-cut wooden frames (RostockMax Delta printers):** The RostockMax 3D printer uses almost all laser-cut wooden parts for its construction. (See Figure 12-10.) Only the vertical upright sections are aluminum extrusions. Channels in the wooden sections accept a standard nut, and bolts clamp parts together to form a solid structure. (See Figure 12-11.)



FIGURE 12-10:
A highly precise
jigsaw puzzle of
wooden laser-cut
sections forms
the frame of the
RostockMax 3D
printer.

Electronics, power supplies, and wiring can be mounted to specific sections of the wooden frame to achieve a neat, tidy look for the finished 3D printer (see Figure 12-12).

FIGURE 12-11:
The sections are assembled with trapped nuts and bolts.

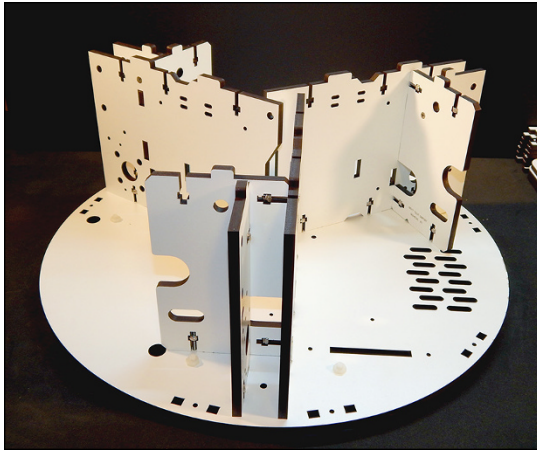
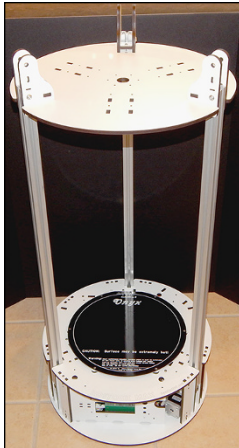


FIGURE 12-12:
During assembly, aluminum extruded sections are fitted to achieve vertical height for the Delta printer.



» **3D-printed frames (3DR Delta printers):** The 3DR Delta printer is a lot smaller than the RostockMax; its frame is constructed from a minimal set of 3D-printed parts that bolt together. (See Figure 12-13.)

At the top is a set of three identical parts that can be printed in whatever colors you choose. Electronics, wiring, and sensing components are fitted onto the 3D-printed frame construction (see Figure 12-14). The result is a strong frame on which you can fit the rest of the printer parts. (See Figure 12-15.)

Because the printer is mainly 3D-printed and able to print its own parts, the 3DR Delta printer is easy to change, evolve, or even scale up or down in whatever way you require.

FIGURE 12-13:
Three identical
3D-printed
sections have
vertical upright
aluminum
sections fitted
and can be bolted
together.

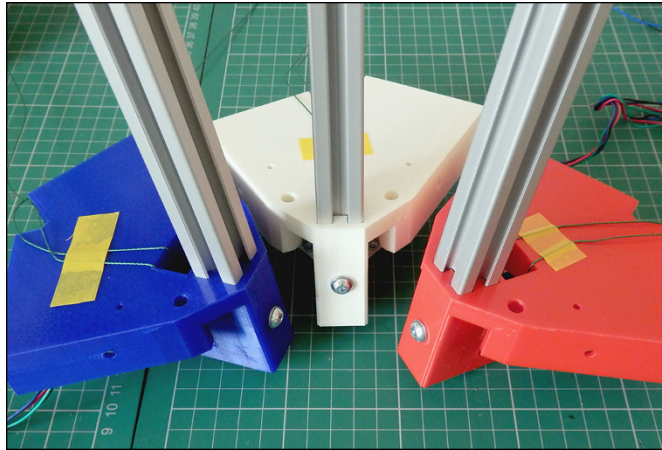


FIGURE 12-14:
The three motors
that drive the
printer are
attached to the
3D-printed parts.

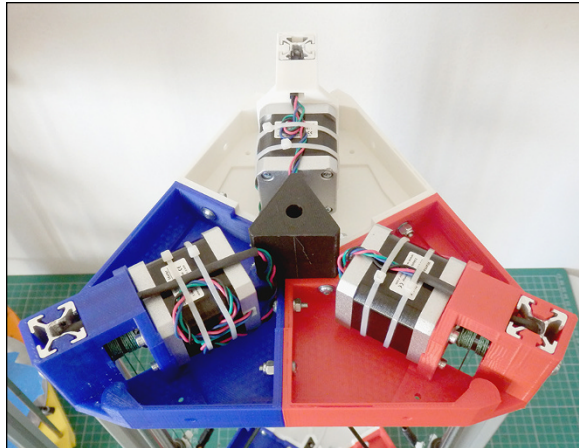
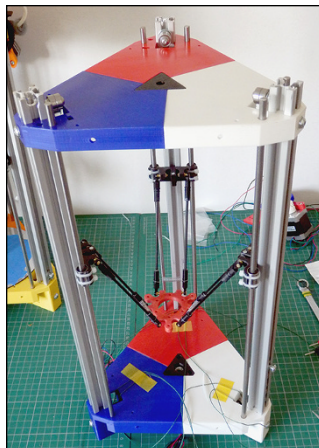


FIGURE 12-15:
A 3DR Delta
printer frame.



Assembling the Moving Axis

Below and in the next chapter, I use the Prusa MINI as an example of a modular 3D-printer kit that can be assembled by anyone. There are only a few main frame parts that need to be bolted together and a number of wiring connections that require plugging in to the correct positions on the electronics control board. The Prusa MINI assembly manual is already an excellent guide to the construction and use of the machine, so please think of what I offer here as an overview to show you how straightforward it can be to assemble a modular desktop 3D printer. It should hopefully give you the confidence to decide if this is a good route to take when sourcing a 3D printer for your needs.

As is the case with most 3D-printer kits, the Prusa MINI comes in modular parts. One of those parts — a major one, in fact — is the Y axis and build platform. (See Figure 12-16).

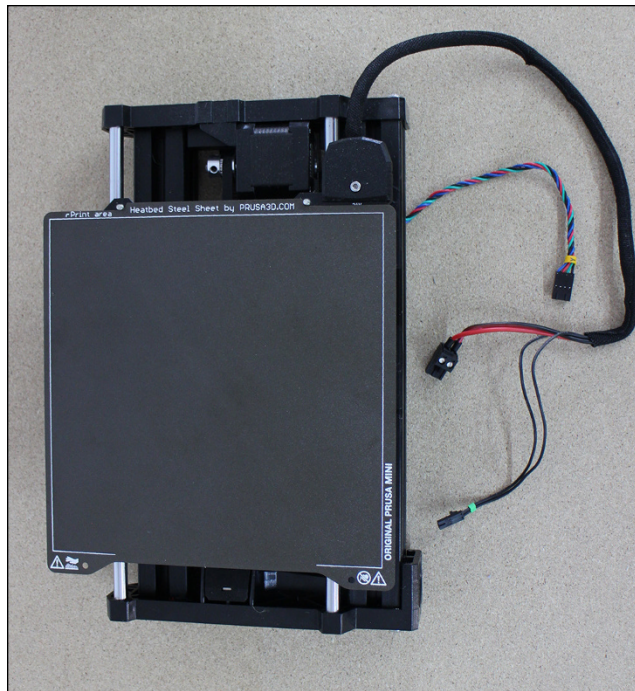


FIGURE 12-16:
The Y-axis
assembly of the
Prusa MINI

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The build platform shown in Figure 12-16 is magnetically secured to the heated bed; a stepper motor moves this assembly back and forth in the Y axis direction along smooth 8mm steel rails using LM8UU linear bearings. Connections from

this Y-axis assembly are for the stepper motor (4 wires), the bed heater (2 wires), and a temperature sensor that measures how hot the build surface actually is — crucial information if you want the print process to succeed.

One of the first tasks for assembly is to fit the LCD screen and user controls interface to the Y-axis frame. This particular task requires only a single bolt. (See Figure 12-17.)



FIGURE 12-17: Fit the LCD screen and controls module using a single bolt; the screen can then be angled as required.

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You'll connect the ribbon cable from the LCD screen and user controls shown in Figure 12-17 to your electronics a little later on, but for now let's take a look at the X- and Z-axis assembly. (See Figure 12-18.)

The X carriage moves left to right along round smooth steel rods, along with the Y front-to-back motion that positions the printer nozzle in any location on the build surface. The entire X carriage is also connected to the Z axis that is slowly moving the printer nozzle up and down to provide the third dimension to our 3D printer.

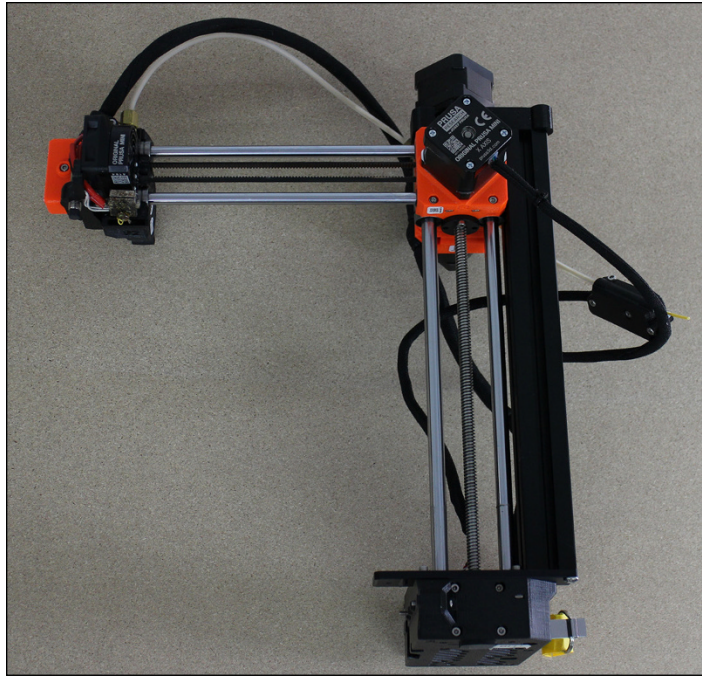


FIGURE 12-18:
The X and Z axis
of the Prusa MINI.

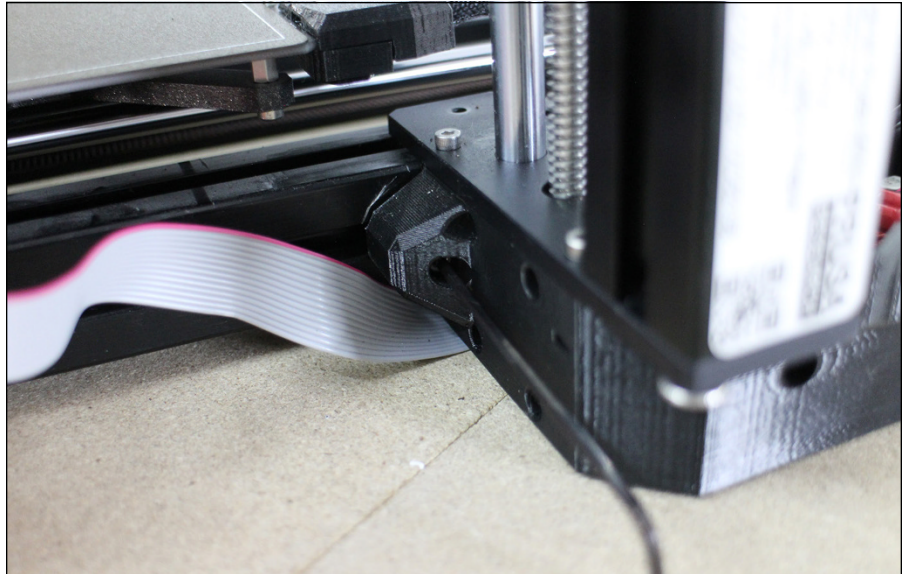
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Connecting the Y Carriage to the X and Z Assembly

You only have to worry about three M3 bolts when fixing the Y carriage assembly to the X and Z axis. Alignment is important, but the Z and X carriages have the electronics control box also fitted so you can use it as a spacer to align at the correct position on the Y-axis carriage. Just place the two parts next to each other and bolt them together. (See Figure 12-19.)

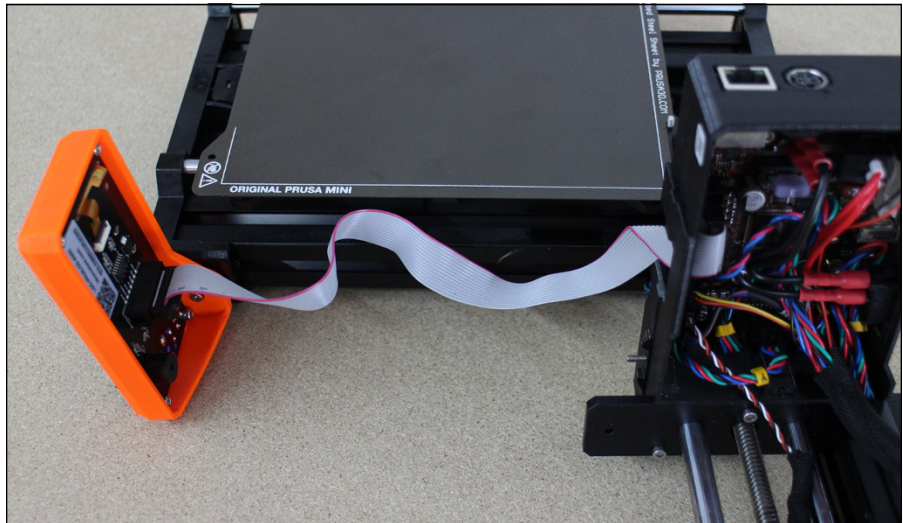
When the main frame is bolted together, you'll need to make a number of wiring connections; these are all labeled as individual tags on the wires and correspond to locations on the electronics control system. For an example of how easy this is, you can connect the LCD and user control module via a multi-way ribbon cable to the electronics. (See Figure 12-20.) All of the cables are secured to the frame with zip ties at a later stage of assembly.

FIGURE 12-19:
Fixing the two
main modular
carriage
assemblies
together requires
just three bolts.



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FIGURE 12-20:
The flexible
ribbon cable from
the LCD and user
control panel can
now be routed
into the
electronics
enclosure and
connected onto
its connector.



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The motor connections are a single 4-way plug and are labeled with Z, X and Y tags; these just need to be fitted into the corresponding positions on the electronics control board. The heater connection for the build surface, temperature sensor, and corresponding connections for the hot-end nozzle are also connected to the control electronics. (I show a few more examples in Chapter 13, but I'm sure you can already see this is not a complicated task.)

And that ends our quick tour of the assembly process. You should now be more familiar with the overall modular construction of a desktop 3D printer.

Sensing the Home Position

To understand where its print head is, a 3D printer needs a reference point, called the *home position*. Before a 3D printer begins a print job, one of the very first actions it performs is locating its home position. This action is very important, because the print head could be nearly anywhere in the space above the build platform. To ensure that the print head is at a known position, use a sensor or switch fitted at the ends of each axis. The switch is triggered when the print head reaches home position. (See Figure 12-21.) A PINDA probe (shown on the center left in Figure 12-21) is aligned so it has a small gap before the nozzle touches the print bed; this gap is set and calibrated from a series of magnets fitted in the build surface. This PINDA probe not only detects the correct starting height for the nozzle to start extrusion, but it also probes nine points over the build surface plate and can compensate for a deformed or non-level surface.

When the frame and moving axis systems are fitted together, the wiring of the electronics can begin. The process isn't as complicated as it may seem. The electronics are modular, and wiring is straightforward. I walk you through that part of the process in Chapter 13, along with an overview of 3D printer control electronics and the embedded software (firmware) that controls the 3D print process. Your desktop 3D printer is now just about complete.

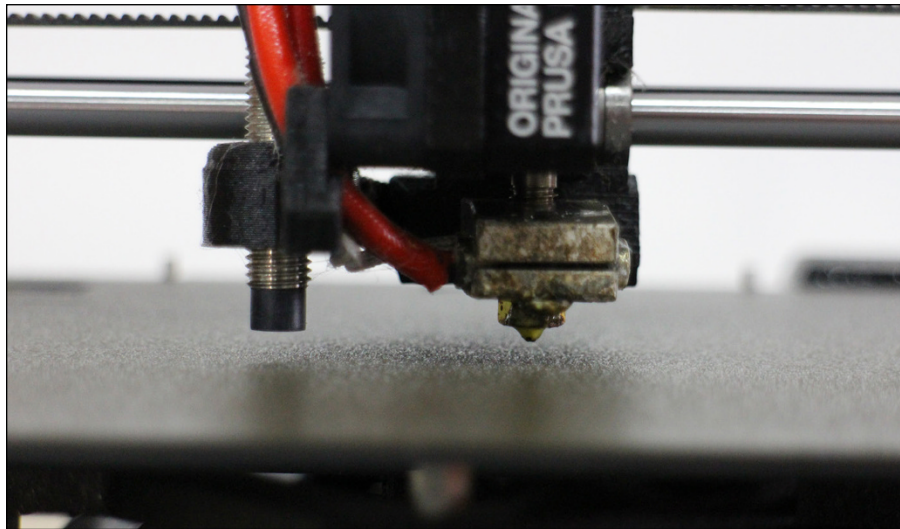


FIGURE 12-21:
A noncontact
PINDA probe
sensor fitted to
an assembled
Prusa MINI 3D
printer.

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IN THIS CHAPTER

- » Working through 3D printer control electronics
- » Connecting to the control electronics
- » Carrying out your first Power On checks
- » Configuring setup for the Prusa MINI firmware

Chapter **13**

Understanding 3D Printer Control Electronics

The electronics and firmware running a modern desktop 3D printer represent thousands of man-hours of open-source development and refinement to achieve an operational machine. In this chapter, I walk you through some of the history of common RepRap-based electronics, have you look at the firmware Marlin 2.0 used to drive the electronics, and explain how everything comes together to make a 3D printer. I also guide you through wiring, upgrades, and optional parts, along with the sensors and motors that provide for the all-important thermoplastic extrusion and mechanical movement.

In Chapter 12, I describe in some detail the assembly of a modular kit 3D printer and touch on the wiring into the printer's control electronics. In this chapter, I focus more on the purpose of the control electronics and dive into more details about the various sensors, displays, and extruder options.

3D Printer Control Electronics

Reliable and stable electronics — that’s what you need for a 3D printer. Electronics are the very heart of the complex mechanical operation and must be dependable throughout the many hours they have to work while you’re waiting for a complex print to finish.

RepRap electronics were born from the open-source Arduino project. The result of their concerted efforts was an industry-standard embedded control board that can be used for all sorts of applications, from industrial control systems, robotics, and hobby electronics to quadcopter self-flying drones and wearable electronic devices.



TECHNICAL
STUFF

The control software running on a 3D printer is known as the *firmware*; it translates instructions from the sliced model data into the print head movements that serve to extrude plastic into the desired shape. The firmware is an essential aspect of every 3D printer; it’s the control operating system much like Windows on your PC (or Mac OS on a Mac computer) and it handles everything from print file selection to exact motor control and temperature regulation of thermoplastic extrusion. The firmware also takes care of controlling fans for cooling the printed part, sensing the temperature of the nozzle and thermal control of the print bed. Firmware also keeps an eye out for head crashes (where the moving print nozzle hits a part of the model being printed and becomes misaligned) and many more functions.

The electronics for RepRap-style 3D printers have historically taken the form of either a standard Arduino board and a cover shield containing the specific 3D printing electronics, drivers, and sensors or a dedicated all-in-one set, still based on Arduino but having various customizations for RepRap and other 3D-printing platforms. In newer printer models, dedicated single board sets of 3D printer control electronics provide the power, but such boards are still often based or evolved from the original RepRap + Marlin control platform.



REMEMBER

Don’t get too overwhelmed by the many choices of RepRap/3D printer electronics. They all provide essentially the same set of functions and usually run similar firmware. They’re often Arduino based, so they’re relatively common and compatible, varying mainly in terms of features and the number of outputs. If you’re looking beyond the standard electronics listed in this chapter, just make sure that the design supports modern firmware such as Marlin or Sprinter before you buy.



TECHNICAL
STUFF

The control electronics used these days in modern desktop 3D printers fall into two distinct categories: legacy 8-bit models based on the Arduino design and the often more powerful 32-bit control sets that feature touch-screen controls and other quality-of-life enhancements. Unless you’re building your own 3D printer, you’ll not have much choice in the type of electronics used in a desktop 3D printer.

The sections below aim to give some background and familiarity to various legacy and modern 3D printer electronics so you can at least be aware of the various functions and spot what may be included in the machine you decide to buy.

Adding RAMPS

To date, the most common type of electronics used combines the Arduino MEGA 1280 or 2560 standard control board and an open-source RepRap expansion board Arduino shield called RAMPS (RepRap Arduino Mega Pololu Shield), conceived by Johnny Russell of Ultimachine. The top of Figure 13-1 shows the RAMPS shield that plugs into the Arduino MEGA board. You can add various user display screens, keyboards, and multiple extruder print heads as required. For more than 10 years of open-source 3D printer development, the RAMPS system formed the basis of mode desktop 3D printers and is in one form or another still alive today.

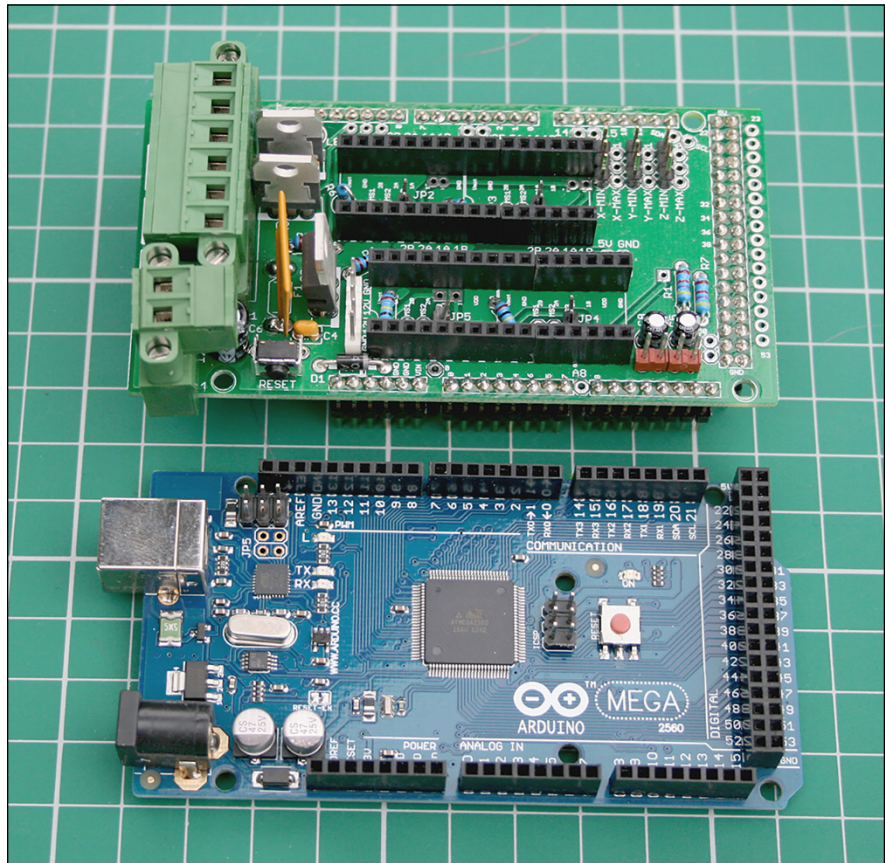


FIGURE 13-1:
RepRap RAMPS
(top) and Arduino
(bottom).

Going the RAMBo route

RAMBo (see Figure 13-2), an evolution of RAMPS electronics, has an all-in-one format and many new features. RAMBo is becoming popular with kit-builders and users, especially in the United States. RAMBo stepper-motor driver devices are permanently fixed to the board, not provided as separate modules. This arrangement lowers the cost, but if a driver device is damaged, the whole board can become useless. If you use separate motor-driver modules (see the “Connecting up cables and wiring” section, later in this chapter, for more on that topic), you can replace a damaged module or upgrade to modules that offer finer step-resolution.

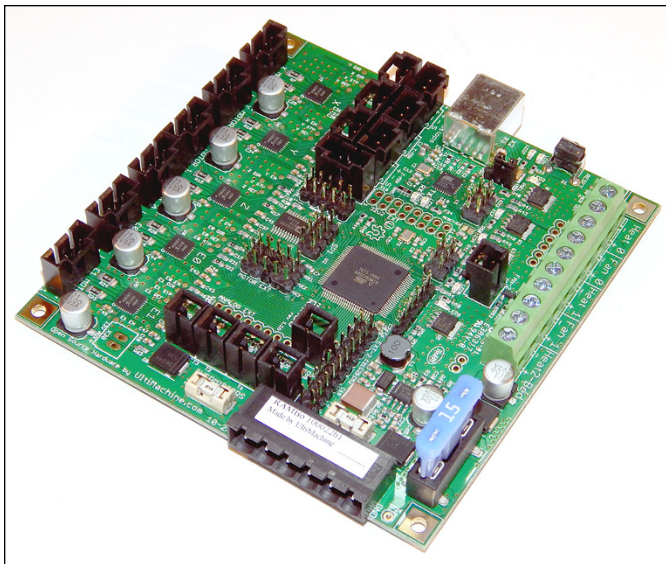


FIGURE 13-2: RAMBo combines the Arduino MEGA and a RAMPS shield in one compact control board.

Selecting Sanguinololu

Sanguinololu (see Figure 13-3) is one of the original easy-to-build electronic sets for RepRap printers. It also happens to be one of the smallest and lowest-cost electronic sets for RepRap and is ideally suited for you hobbyists out there. As with other electronics discussed here, you can expand it further with a full graphic LCD display and memory-card slot to allow computer-free printing. It's very popular; you can build it up at home from self-sourced components. Further evolutions of the Sanguinololu include the Melzi board, designed for mass manufacture using surface-mount components but quite similar in function.

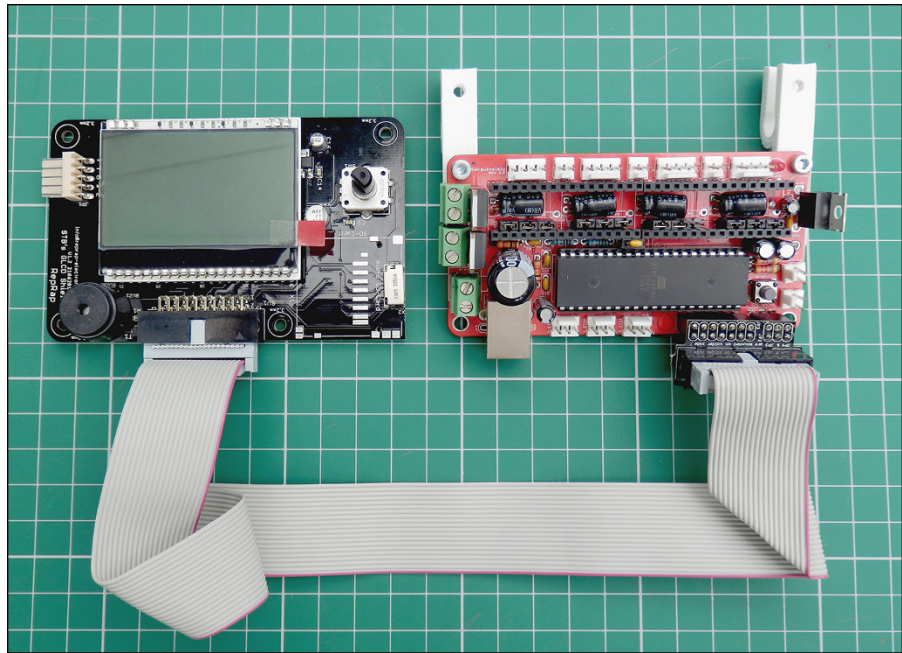


FIGURE 13-3: Sanguinololu, one of the smallest and lowest-cost electronics sets for RepRap.

Minimizing with Minitronics

Minitronics (see Figure 13-4) is an evolution of the Sanguinololu (see the preceding section) that provides the minimum requirements to run a single-extruder 3D printer. It has minimal expansion options but is the most compact electronics package available for RepRap. The Minitronics board is tiny; everything is integrated. The board can be mass-produced and has the lowest component cost, so it's an ideal choice for mass-market, consumer-level 3D printers.



REMEMBER

Even though many RepRap electronics boards are becoming more integrated, it's generally still a good idea to use modular electronics, which can be upgraded or replaced if one part becomes faulty or damaged. You're quite likely to damage a motor driver at some point, so any electronic designs that have the drivers soldered down (instead of contained in a replaceable module) run the risk of being unrepairable.

Rolling with RUMBA

RUMBA (see Figure 13-5) is another integrated board with many options for futureproof (easy-to-upgrade) expansion. It's a good choice for RepRap developers because its modular design allows for change and expansion and, as an added

bonus, it can drive up to three separate extruders. This controller uses stepper-motor modules the same way that RAMPS does. It has an LCD display, memory-card modules, and thermocouple (a very high quality temperature sensor) add-on boards to expand its functionality.

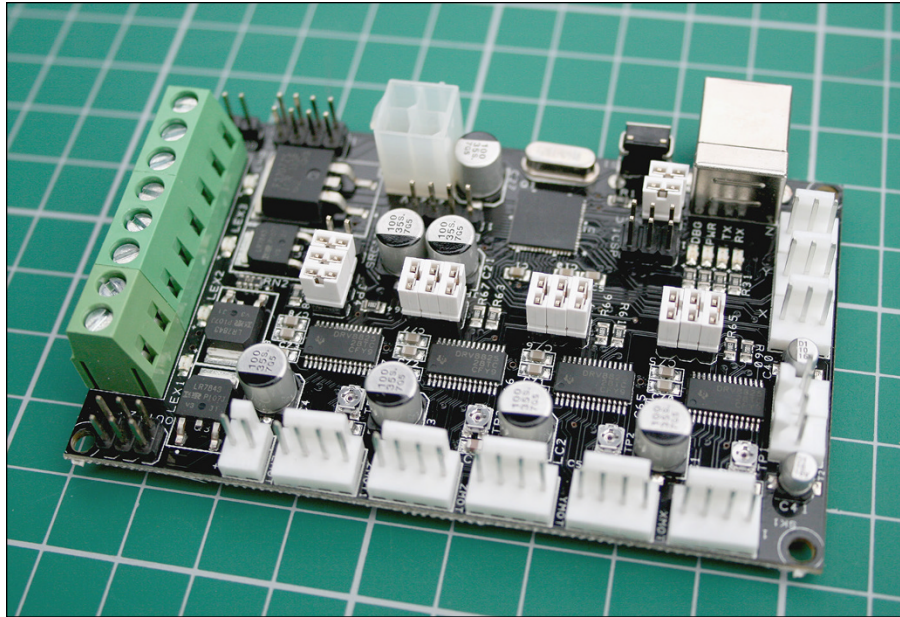


FIGURE 13-4: Minitronics includes the minimum electronics required to run a 3D printer.

Expanding with Elefu-RA V3

The Elefu electronics set is squarely aimed at both developers (because it allows a lot of expansion and flexibility) and novices. The power supply required for this board uses almost any industry-standard PC ATX high power supply unit: Simply plug your ATX connector into the board. All other connections are made via standard screw terminals that are clearly labeled on the board, which allows easy machine wiring with no need to crimp connectors or do any soldering.

Expansion modules include an LCD board with memory card and rotary knob for navigating program settings and printing files without a computer connection. These expansion boards are simply wired with screw terminals. The Elefu design (see Figure 13-6) makes wiring a 3D printer clear and easy; it provides many expansion options and three extruders. It uses its modular motor drivers the same way that RUMBA and RAMPS do.

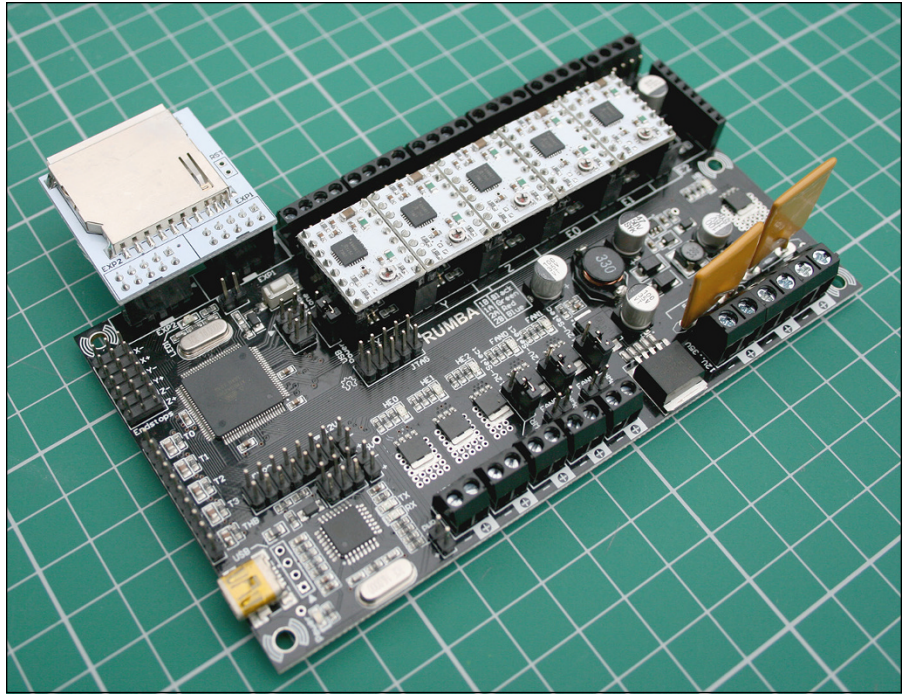


FIGURE 13-5:
RUMBA with an
expansion
adapter for a
memory card.

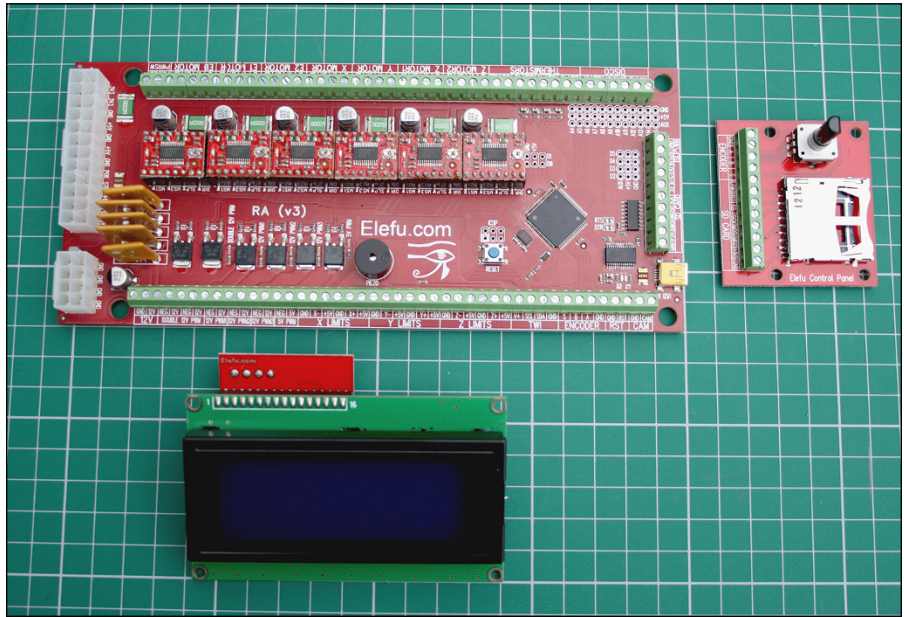


FIGURE 13-6:
The Elefu design.

Total control with Megatronics

Megatronics (see Figure 13-7) is another integrated motherboard, highly capable of expansion. It has three extruder options and is ideal for a developer (and anyone else) who wants a machine with all the options. You can easily add LCDs and keyboards; a memory-card slot is standard.

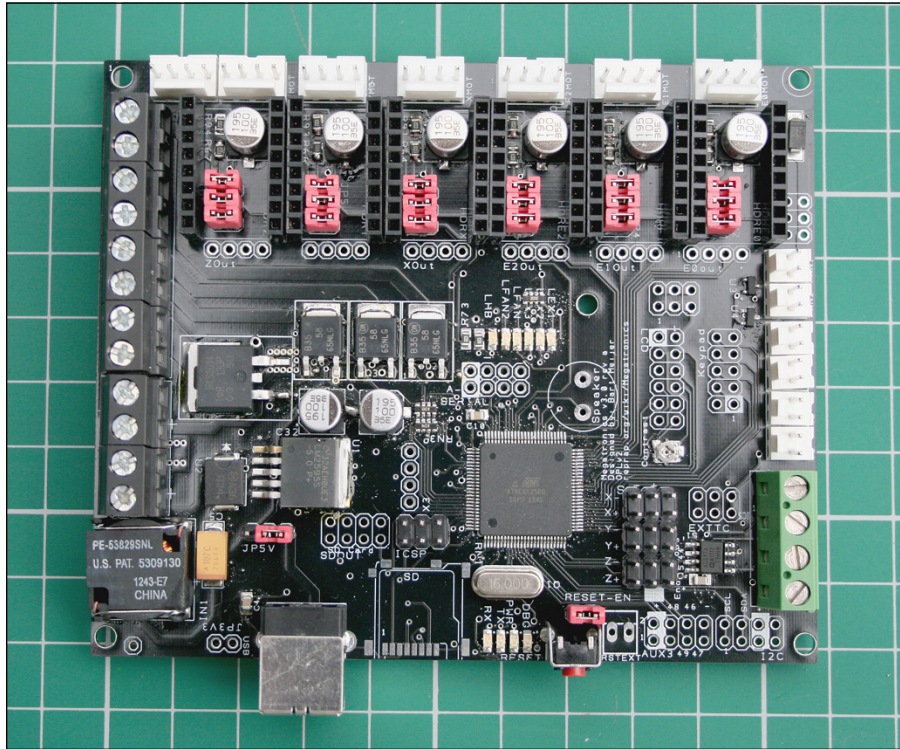


FIGURE 13-7:
The Megatronics
integrated
motherboard.

Megatronics is the bigger brother of Minitronics, discussed earlier in this chapter. It has capabilities similar to those of RUMBA, uses modular stepper-motor drivers, and can run with dual thermocouple temperature sensors — all standard. All the other electronics allow only *thermistor* (basic lower temperature measurement) sensing, which is adequate for most users, but thermocouples can handle much higher printing temperatures (above 300° C), allowing experimentation with exotic materials. Thermocouples provide accurate temperature measurement and come prewired with high-temperature cable.

Prusa i3 electronics

As I am using the Prusa i3 and MINI machines as examples of common desktop 3D printers, the electronics used in these machines represent a leap in terms of technology and functionality from earlier machines based on Arduino 8-bit microcontrollers and simple text-only display interfaces (see Figure 13-8) and the more advanced 32-bit ARM control system that looks a lot more like your smartphone display. (See Figure 13-9.)



FIGURE 13-8: The Prusa i3 MK3 control interface is showing its age but is still a very capable system.

Prusa Research a.s.

Advanced 32-bit, arm-based electronics

As the demands of desktop 3D printing have expanded, along with users' desire to have more interaction with the machines, a new generation of powerful ARM-based, 32-bit electronics are now being used in more recent 3D printer designs. These new control electronics can be networked or wirelessly connected; they run sophisticated full-color screen displays, and they print quickly and smoothly. This area of 3D-printing development is moving very fast indeed. Users are demanding multiple tool heads that operate quietly, incorporate fast motor drives, and offer high-quality printing, thereby pushing powerful microcontrollers into 3D printing. Prices are falling, which makes it more likely that you'll see advanced electronics in your next desktop 3D printer.



FIGURE 13-9:
The Prusa MINI
uses a 32-bit ARM
Buddy board
integrated
motherboard and
color LCD screen.

Prusa Research a.s.

The more powerful ARM-based “Buddy board” provides significantly more processing power and quality-of-life upgrades. The 32-bit electronics used with the Prusa MINI has a standard USB connection for a memory stick and a graphical color LCD screen that can show a preview of the models being printed. (Refer to Figure 13-9.) The information displayed also shows the print time, weight, and material used along with the type of material set by the slicer.

Another example of a high-end 32-bit electronics control system is the Duet Wifi motherboard. (See Figure 13-10.) This control platform is specifically designed to handle multiple extruders at the same time with a high resolution color LCD screen and a sophisticated user interface.

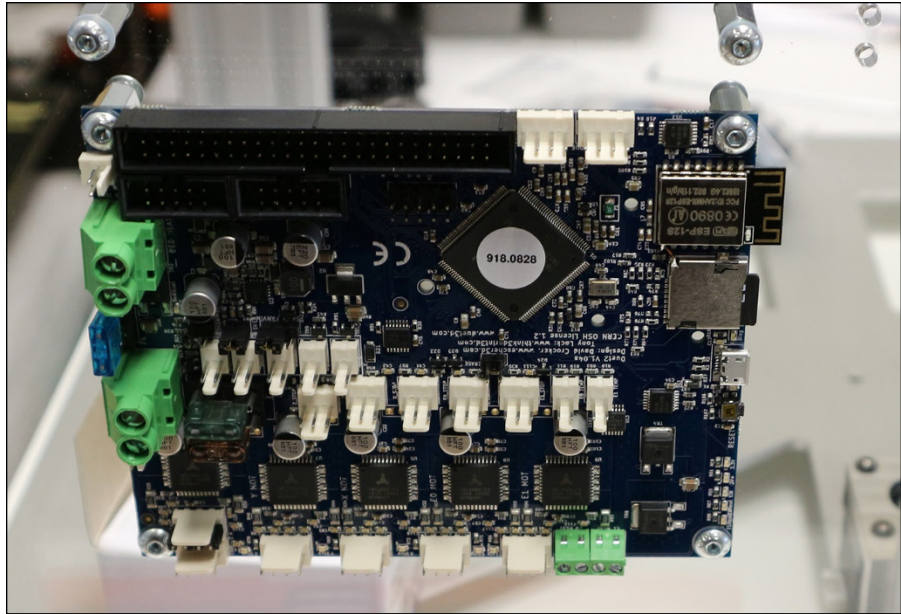


FIGURE 13-10:
The Duet Wifi
32-bit multi-tool
integrated
motherboard.

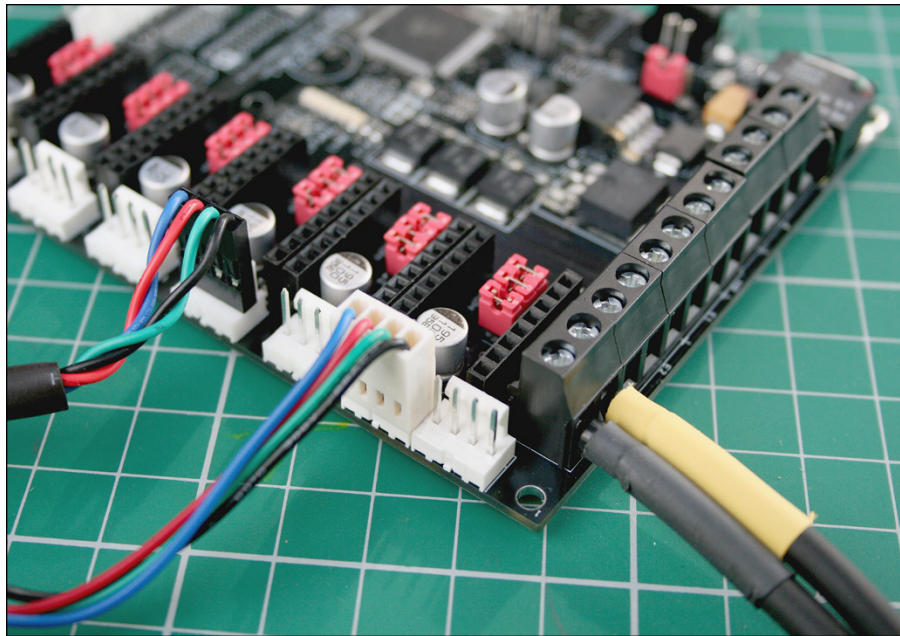
Adding Electronics to Your 3D Printer

Chapter 12 is all about assembling a frame for your 3D printer from modular sections. This chapter builds on that work by showing you how to make the necessary electrical connections to your 3D printer. If you have a ready-built 3D printer, don't think this chapter section is a waste of your valuable time; the information here will still be useful for identifying the common components that are all connected to most 3D printer electronics. This section focuses on the sensors, heating elements, and the main electronics control board. Upcoming sections discuss these assemblies in more detail.

Preparing for electronics assembly

Before you start assembling the electronics, make sure that you have all the components you need. It's highly likely that your electronics kit came with prewired components. The motors often have four-way connectors fitted, whereas the position sensors often have three-way connectors. (See Figure 13-11 for examples of the common types of electrical connections.)

FIGURE 13-11:
Crimped motor
connections and
plastic connector
shells of various
styles.



Connecting up cables and wiring

Even with a full, ready-to-build kit, you may still have to connect various components and devices to the electronics — and that sometimes means crimping connectors or doing a little soldering. The Prusa MINI kit does not require any crimping or soldering, but some other kits may do so; do check and make sure it's something you are happy to do before ordering. Below I highlight some of the most common types of electrical connections when fitting cables, sensors, heaters, and fans to the control electronics.

One of the simplest connection types is a screw terminal. Often used for high-power connections such as the power supply input, hot-end heater, and heated bed, a screw terminal can also be used for motors, fans, and lighting.



TIP

It's a good idea to use bootlace ferrules when attaching wires to screw-terminal connections. (Yes, they are named for those plastic sleeves that are crimped onto the end of shoelaces to keep them from unraveling.) The ferrule, like their shoelace counterparts, constrains the wires so that their strands don't spread out when the screw is tightened. Ferrules create a more secure connection and reduce the chances of frayed cable strands, short circuits, and burned connections.

Another common type of connection is the crimped multiway terminal (refer to Figure 13-11 earlier in this chapter), which is inserted into a plastic shell to form a connector that can be plugged into a mating set of pins on the electronics.

Multiway terminals are often keyed so that they can be inserted only one way; others use plastic shells so that they can't be rotated or accidentally offset on the mating connection.



WARNING

When attaching any connection, make sure that it's oriented correctly.

Many other types of connectors can be used for electronics, power supplies, and other board modules. When you buy a full kit, connectors and wiring often come premade; check with the supplier if you have any concerns about the wiring of the electronics. Small mistakes can destroy one of the most expensive parts of your new 3D printer.

Selecting the correct gauge of wiring is also important for safe, reliable operation. A NEMA 17 stepper motor, for example, has 7/02-gauge wires fitted. Seven strands of 0.2mm wire are twisted together to form each cable. This size of wire is usually suitable for connecting sensors, fans, and LED lighting. Connections to hot-ends, heated beds, and power supplies require significantly higher-rated cable. Figure 13-12 shows examples of common wire gauges used in various aspects of a 3D printer. You will need to use an appropriate size of wire depending on the power required as well as the voltages and current used on your particular set of components. Check with the manufacturer. A kit machine should come with the correct set of wiring, but if you are building your own, please do further research to ensure you use the correct rated wiring size for your requirements.

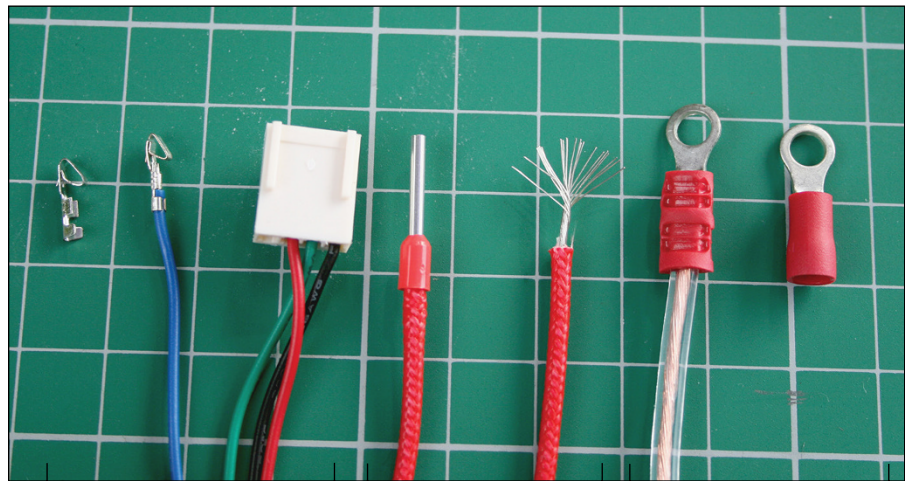


FIGURE 13-12:
Common
wiring types.

Stepper-motor wiring
(7/02 gauge) with crimp
terminals

Hot-end connection with
thicker red silicon-coated
wire and ferrule

Power-supply or heated-
bed wiring (ring-terminal
connection)

Moving axis positional sensors

All 3D printers need to know when the print nozzle is at the home position, usually the front left point of the build surface at $X = 0$, $Y = 0$ and $Z = 0$. In order for the electronics to know when each carriage motor has driven the axis to the end, an end-stop is required. In the case of the Prusa MK3 and MINI machines, the end stops are actually detected by the motor current stalling at the end of travel. This method of no physical end-stop sensor is not on all machines, so your 3D printer or kit may have an optical, mechanical switch, or magnetic position sensor, as shown in Figure 13-13. All such positional sensing components perform the same operation of detecting the end position of a carriage in the X, Y, or Z axis. Read more about position sensors in “Connecting to the control electronics,” later in this chapter.

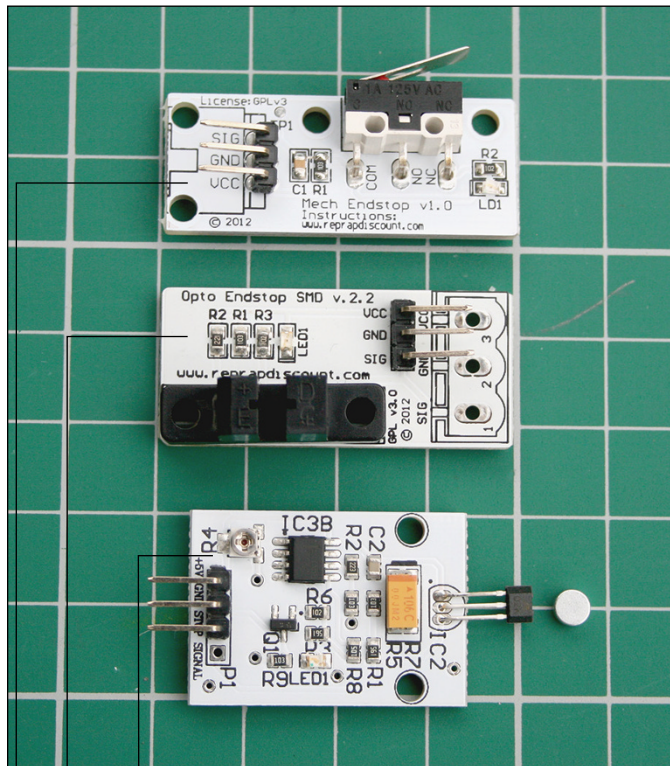


FIGURE 13-13:
Positional sensors set the home position for the printer.

Magnetic hall-effect sensor
Optical light
Mechanical switch

In modern 3D-printing kits, you simply need to attach various ready-wired connections from motors, sensors, and heaters to the corresponding connection on the electronics control board. The following steps explain the common connections but remember to check the exact details of the kit you are building.



TIP

If your 3D print head crashes into the model being printed or if anything else stops the expected motion of an axis, the motors may drive the print head into either the end-stop sensor or the opposite end of travel. If this happens, you may hear a loud grinding noise, which can be alarming the first time it happens. Don't panic. The 3D printer will often either stop or try to do a home XY position reset and continue or inform you that a crash has happened. Sometimes you can restore the print operation, but all too often the print must be stopped, removed, and started over. This is sure to happen to you at some point; it's a little like a paper printer jam; remove and try again.

Checking and fitting the filament sensor

I am a big fan of filament sensors on desktop 3D printers. Not all machines are fitted with one as standard and some are optional extras, but they provide one of the most useful sensing functions. A filament sensor's job is to detect when the filament spool is about to run out of material; it then pauses the print, sounds an alarm, asks you to fit another spool of filament, and then continues the print job. Without a filament sensor, you either have to guess whether you have enough filament remaining on the spool, weigh the spool, or be prepared to keep on checking the printer and catch the end of material.



REMEMBER

A 3D printer without a filament sensor will quite happily keep on printing without any material entering the extruder and so (no surprise here) nothing will be extruded out of the nozzle. This can be quite annoying and waste a perfectly good print just because you ran out of material on the spool. (See Figure 13-14.)



TIP

If you can fit a filament sensor to your 3D printer, take the option or better still look out for a machine with one already installed. It'll pay for itself several times over and will maximize the use of filament on a spool.

Connecting to the control electronics

Chapter 12 showed you how to complete the mechanical construction of the Y axis and heated bed; if you have that out of the way, it's time to make the electrical connections to the control system. This really is very straightforward, as shown in Figure 13-15. Here, the main heater wires and thermistor (temperature sensor) connections are plugged into the electronics. Cable wiring can be routed and secured toward the end of the build.

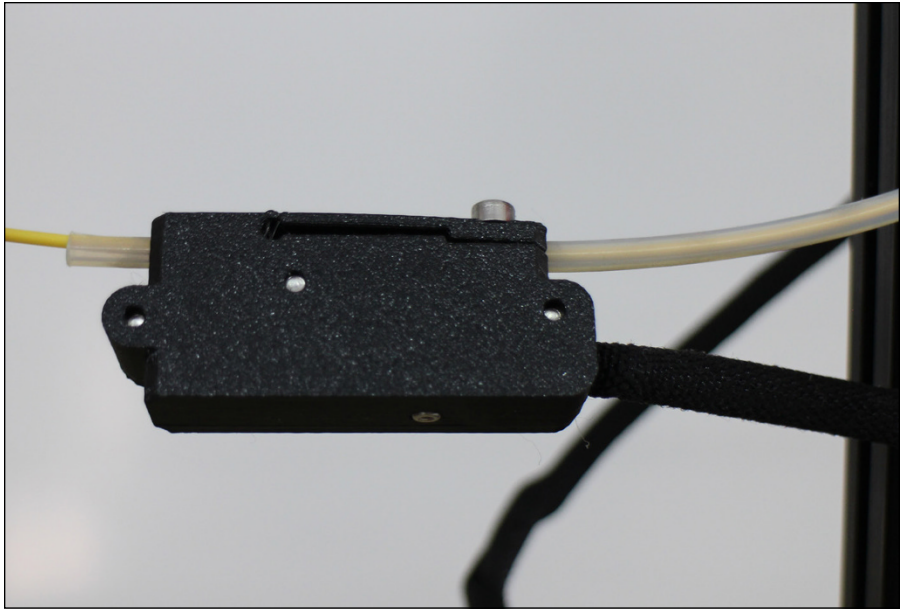


FIGURE 13-14:
The in-line filament sensor to check when your spool is about to run out of material during a print.

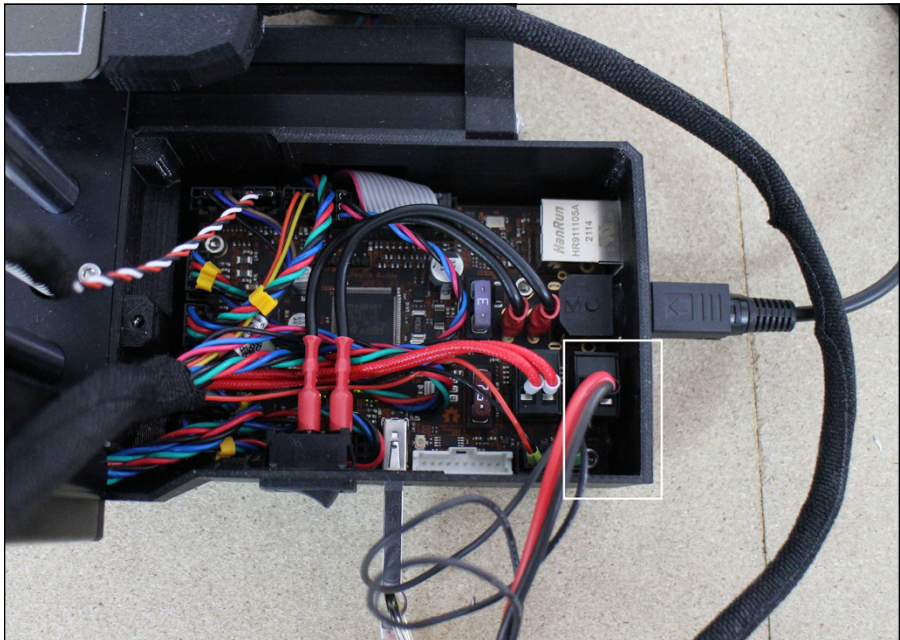


FIGURE 13-15:
The heated bed wiring and temperature sensor connected to the control electronics.



REMEMBER

You don't need to level the bed yet; leveling is a required part of calibration later, when the machine is ready to print.

The hot-end heater and temperature sensor are connected in a similar way (see Figure 13-16).

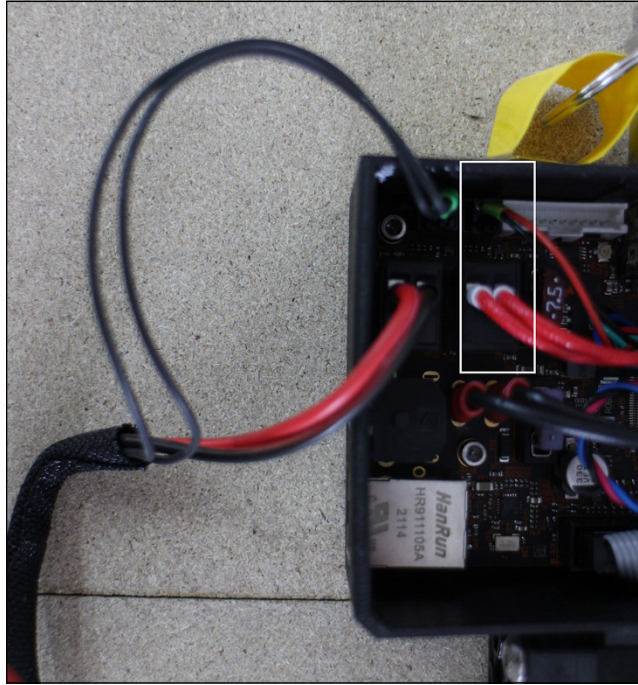


FIGURE 13-16: The hot-end heater and temperature sensor connected up to the control electronics.

The wiring from the filament sensor shown in Figure 13-14 can now be attached to the control electronics (see Figure 13-17).

All the stepper motors have the same four wire connectors. Carefully check you are fitting them to the correct points on the electronics control system. (It will be described in the build assembly manual.) In Figure 13-18, the Y axis (marked) is being fitted. Repeat for all other motors.

After fitting the remaining connections, it's time to route the cables and fit the electronics cover. (See Figure 13-19.) With that done, just connect the external power supply and switch on the printer.

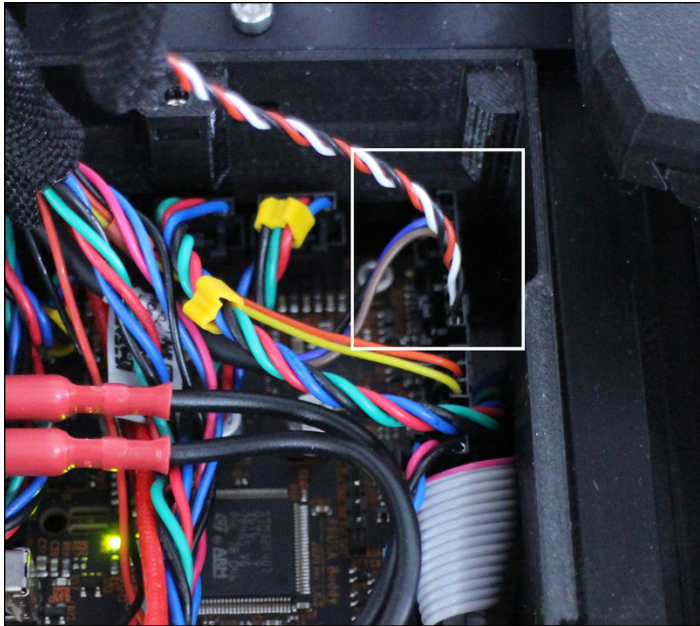


FIGURE 13-17:
The optional filament sensor connection to the control electronics.

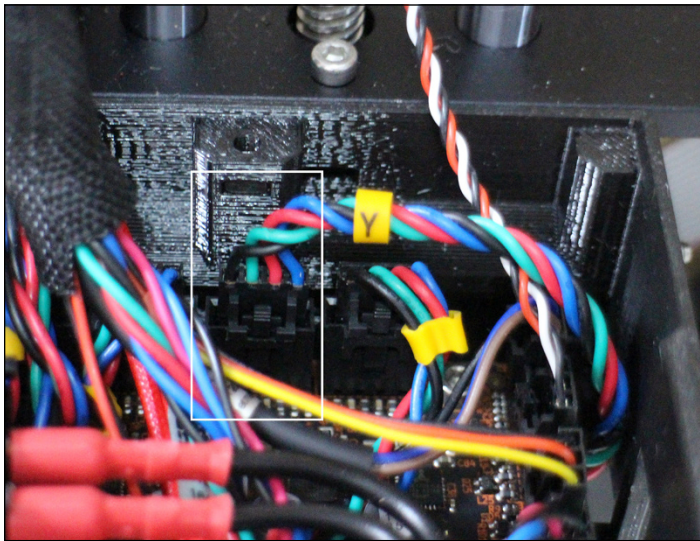


FIGURE 13-18:
Each stepper motor Y, X, Z, and E (Extruder) will need to be connected to the correct location on the electronics.

FIGURE 13-19: Fit the cover over the electronics, and you are ready to power on for the first time.



Doing Your First Power On Check

If all has gone well with the assembly, you can power on, and the Prusa MINI 3D printer should load and present the Wizard setup. (See Figure 13-20.)

Select the wizard to start testing the printer setup. It will check the fan connections and then move on to further checks of the motors and heaters.

If all is well the wizard will continue on to the next test until all the most important functions are checked and confirmed as working.

During all these self-checks, the 3D printer electronics are detecting the position of the motors and temperature of heaters. Many 3D-printer kits will have sensing position modules for the motor travel on each axis, so they will be checked as well. (See Figure 13-21.)

Selecting position-sensing modules

On almost every 3D printer, the electronics need to know where the home position is. To find out, the electronics slowly drive each axis in a known direction until a limit switch or sensor is triggered, which tells the electronics where 0 is on axis. When the extruder carriage is in the home position (0,0,0), you can start a print job with the assurance that the printer knows where to begin the many 3D moves that start and complete the print job.

FIGURE 13-20:
The first power on will guide you through a few setup options, and then the wizard will check whether the construction has been completed correctly.



Prusa Research a.s.

FIGURE 13-21:
The firmware wizard will check axes movement including the end-stop position sensing.



Prusa Research a.s.



REMEMBER

3D printers use the initial home position as a universal reference point. From the moment the home position is defined, every move is calculated as a number of steps on each axis away from that point and each step helps position the print head in 3D space. Unfortunately, no feedback mechanism confirms a component's location. If an axis, carriage, or print head is knocked askew or goes out of alignment compared with where the electronics think it should be, the printer continues to print, but the model is misaligned and usually ruined, as the melted plastic is deposited in the wrong places. The 2D dot-matrix printers of the past kept cluelessly printing even if the sheet of paper was out of alignment, and the same situation occurs with 3D printers. Even many professional units aren't yet intelligent enough to know when they're going wrong or out of alignment.

To keep the print job on track (so to speak), the example build in this book uses three main types of positional sensors (refer to Figure 13-13):

- » **Microswitch:** This build uses a simple microswitch (shown at the top of the figure). The carriage mechanically presses into the switch, which sends a signal to tell the electronics that the carriage is home.
- » **Optical sensor:** An optical sensor (shown in the center of the figure) breaks a beam of infrared light that tells the electronics that the carriage is in the home position. Because this sensor is a noncontact switch, it's considered to be more reliable than a mechanical microswitch.
- » **Hall-effect sensor:** The most sophisticated form of positional sensing is a hall-effect sensor (shown at the bottom of the figure) that detects a magnetic field. This sensor is very accurate, with highly repeatable functions, and it's noncontact. All you need to do is fit a tiny magnet to the carriage or moving axis and place the sensor in the home position. When the magnet comes within a specified distance of that position, it triggers the home signal to the electronics. This type of sensor features a small rotary knob that you can turn to adjust the exact trigger distance of the magnet from the sensor. A hall-effect sensor is most often used on the vertical Z carriage to set the nozzle a precise distance above the print bed — usually, at a distance no thicker than a sheet of paper.



TIP

You can use any type of position sensor or a combination of sensors. Check to see whether your 3D printer has the option to use a tunable magnetic type for Z-carriage alignment or — as is the case with the Prusa MINI — a PINDA probe (a Prusa *IND*uction Autoleveling sensor).

Understanding power-supply requirements

Most 3D-printer kits and assembled machines include a certified power supply unit. Selecting a suitable power supply is a key requirement for 3D printers. Desktop 3D printer electronics often run from a single-voltage supply (usually, 12V or 24V DC) and generate other voltages as required. Because a 3D printer melts plastic, home 3D printers can require a significant amount of power to heat the extruder and (most significantly) heat the build bed. These requirements create some challenges — especially when it comes to finding a power supply with enough capacity and wiring capable of passing the required current. Unfortunately, the power supply is one of those areas where very low-cost kits and machines can cut a few corners in terms of quality and reliability. Select a reputable manufacturer with approved power supplies such as the Prusa MINI machines that come with an external power brick to supply the correct power for the machine. (See Figure 13-22.)



FIGURE 13-22: The Prusa MINI power supply is an approved external unit with a single low-voltage connection to the 3D printer.



WARNING

Treat any device that's connected to a household outlet with extreme caution. 3D printers use lower voltages to run various parts of the machine but are still connected to household current via the power supply.



REMEMBER

A 3D printer is likely to be running for several hours at a time; during that time, the main power use is with the heated build surface. The bigger the heated bed build surface, the more power is required to keep it at a stable temperature during the entire print. If you only need to print small parts, a machine like the Prusa

MINI with its smaller print area has a lot of advantages at a lower running cost. Some machines have a massive 400mm × 400mm build area — which sounds great — but they require an exponential level of power to heat that surface compared to a smaller machine. This is where having two different sized 3D printers is often a good idea.

Configuring Firmware

In the early days of desktop 3D printing, you were expected to download a set of generic printer control software; manually configure every single setting; then compile, test, and tune over and over again until the machine limped into life and eventually was tuned well enough to print out something. Luckily now most 3D-printer manufacturers not only do all that hard work for you, but they install and configure the firmware directly onto the electronics for you.

And yet . . . there are still plenty of 3D printers, RepRap designs, and community-based projects that do require some firmware configuration and setup. Just to make sure I'm covering all the bases in this book, I've included the following sections as a guide to updating and configuring RepRap (Marlin) based firmware on 3D printers where Arduino or similar microcontrollers are being used.

For our Prusa MINI, all of the important calibration, thermal profiles, and print quality tuning can all be done using just the machine controls. (I cover that calibration process in Chapter 15.) If you don't have all that much interest in the inner working of the firmware / software powering your desktop 3D printer, feel free to skip the rest of this chapter and move onto Chapter 14.



WARNING

Making changes to the firmware of a 3D printer can be dangerous and cause damage to your 3D printer or worse. Many software checks and settings try to catch dangerous and out of control conditions, but if they are disabled or another fault occurs, your 3D printer may not be safe. Do not make any changes to a 3D printer if you are not completely sure about what you are doing. Always check whether the manufacturer has updates for your machine and consider whether you should be upgrading to the latest release or not. If in doubt, do not make any changes you don't understand and check with the manufacturer if any faults or warnings appear.



REMEMBER

I have mentioned this before, but here is another perfect place to remind you never to leave a 3D printer unattended. You have temperatures on the nozzle higher than most ovens as well as powerful heated build plates with moving wires that can and will eventually fail due to the constant movement and strain on the wiring. Please be careful.

The firmware of an open-source/RepRap 3D printer, although quite complicated, is designed to accommodate many types of RepRap printers — and even different systems of movement. The important part lies in configuring your chosen printer correctly. I could easily write an entire book about just the firmware used on a RepRap 3D printer (and many resources are available for this aspect of 3D printer setup), so in this section, I'm going to limit the discussion to a few key pointers on what to change in the firmware as you calibrate your machine. If you bought a kit or decided to buy one of the machines mentioned in this book, a configuration file is probably available for download, or you can find some settings online and enter them.

Marlin(1) and now Marlin 2.x firmware for RepRap is one of the most common types of firmware and is also easy to use. To compile changes and upload new firmware to your electronics, you need to install the Arduino integrated development environment (IDE). Version 023 is the one used most often, but more modern releases of the Arduino IDE (called 1.0x) can be used for many versions of Marlin.



Sooner or later, you may have to change some settings on your RepRap 3D printer, so taking a closer look at the Arduino tools and language is worthwhile. The Arduino software is available at <https://www.arduino.cc>. You can find a master version of the Marlin firmware provided by project maintainer Scott Lahteine (with contributions by many individuals, including the original creator, Erik van der Zalm) at <https://github.com/MarlinFirmware/Marlin>.

Looking at one configuration example (Prusa i3 firmware)

For an example of one of the most popular RepRap desktop 3D printers and electronics sets, here's a short guide to getting the Marlin firmware running on your RAMPS electronics for a Prusa i3 MK2 machine.

The process can be divided into four easy stages:

1. Downloading and installing the Arduino IDE.
2. Downloading and extracting the Marlin firmware.
3. Editing the Marlin firmware for RAMPS and Prusa i3.
4. Uploading the Marlin firmware to the RAMPS electronics.

The next few sections discuss these steps in greater detail.

This section describes many of the settings you can (and most often do) change to get your 3D printer setup to use the Marlin firmware. Please refer to the more detailed information available at www.reprap.org. The following steps show how to set up a reference Prusa i3 machine; use them as a general guide.

To compile your firmware and upload it to your electronics, you need some applications and the Marlin firmware master. Follow these steps:

1. Download the Arduino IDE from <https://www.arduino.cc>.

Depending on the generation and branch of Marlin firmware you use for your 3D printer, you may require an older version of the Arduino IDE — probably Version 0023. Run this IDE on your computer. Your operating system may automatically install drivers the first time you plug the RAMPS electronics into your computer. If not, follow the onscreen instructions to install the driver. For many recent versions of Marlin, including the custom version used for the Prusa i3 MK2 3D printer, you need Arduino Version 1.0.X or later.

2. Download the Marlin firmware at <https://github.com/MarlinFirmware/Marlin/releases> **by clicking the Download Zip button on the right side of the screen (see Figure 13-23).**

Manufacturers of 3D printers often link to alternative branches of Marlin firmware. The Prusa i3 MK3 firmware, for example, is currently located at <https://github.com/prusa3d/Prusa-Firmware/releases/>.



TIP

Before editing or changing the firmware, look at the manufacturer's settings or configurations, which often do all the hard work for you. If a ready-to-use firmware version is available, use it as a starting point.



REMEMBER

Make sure that the firmware is configured correctly for the electronics and components you've decided to use. Hot-ends, extruders, and even motor types require changes in the firmware configuration file we discuss in the next section.

3. Extract the Marlin firmware directory from the .zip file you downloaded.

There are a lot of files in this .zip package, but the main file you'll be changing is `configuration.h`. This file holds most of the key settings for the 3D-printer configuration and electronics setup you will require. You can edit this file in almost any text editor, even applications like Microsoft Word or OpenOffice, but an ideal application is TextPad.

Editing the Marlin configuration.h file

Editing the configuration file is (again, no surprise here) the heart of configuration. This section provides an overview of the process and specific recommendations.

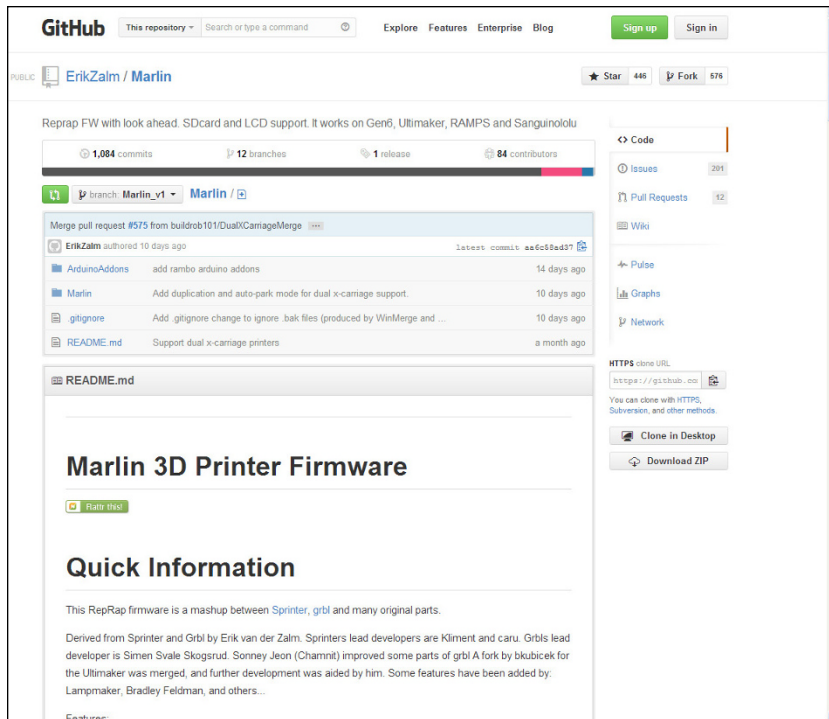


FIGURE 13-23:
GitHub is the
master repository
for the Marlin
firmware used on
RepRap.



WARNING

The `configuration.h` is a text file in computer programming language. Don't fundamentally change its structure or add items; if you do, the file won't compile and operate properly.

When you look at the contents of the file, you see a lot of helpful comments in the code that start with a double slash (`//`). Anything after the double slash is a comment that the firmware ignores; it's there only to help you configure your machine and remember why you made specific changes to the options I discuss later. You may want to add a comment so you can remember why you made the alteration.

Note that some of the code is *commented out* — with `//` in front of it. Such code is inactive; you may have to reenable lines and disable others, as indicated in the comments. Normally, you do so only for nonstandard settings, but this capability may be important for the electronics type you're using with your RepRap printer.

Another key setting in firmware is a `#define` value, which is an important way to let the firmware know what parts of your machine are enabled. The firmware needs to know whether your printer has more than one extruder and a heated bed, for example.

At the top of the file are the types of electronics used in the RepRap 3D printer. Here, you see a long list of comments that give each set of electronics a unique number. (Figure 13-24 shows RAMBo as 301 and different versions of RAMPS as 3, 33, or 34.) The following section shows a `#define MOTHERBOARD 80` (again, see Figure 13-24), indicating that this firmware is configured to use RUMBA electronics. If you want to change the firmware to use RAMBo electronics, all you do is use the comments to change the setting to `#define MOTHERBOARD 301`.

FIGURE 13-24:
Changing the electronics number tells the firmware what other settings to use for pin configuration, wiring, and other details specific to that electronics type.

```

// 3 = MEGA/RAMPS up to 1.2 = 3
// 33 = RAMPS 1.3 / 1.4 (Power outputs: Extruder, Bed, Fan)
// 34 = RAMPS 1.3 / 1.4 (Power outputs: Extruder0, Extruder1, Bed)
// 4 = Duemilanove w/ ATmega328P pin assignment
// 5 = Gen6
// 51 = Gen6 deluxe
// 6 = Sanguinololu < 1.2
// 62 = Sanguinololu 1.2 and above
// 63 = Melzi
// 64 = STB V1.1
// 7 = Ultimaker
// 71 = Ultimaker (Older electronics. Pre 1.5.4. This is rare)
// 8 = Teensylu
// 80 = Rumba
// 81 = Printerboard [AT90USB1286]
// 82 = Brainwave (AT90USB646)
// 9 = Gen3+
// 70 = Megatronics
// 90 = Alpha OMCA board
// 91 = Final OMCA board
// 301 = Rambo

#ifdef MOTHERBOARD
#define MOTHERBOARD 80
#endif

//// The following define selects which power supply you have. Please choose the one that matches your setup

```

You can take the same approach to the other settings by taking one of the following three actions in the `configuration.h` file:

- » Changing the `#define` numbers
- » Uncommenting the parts you want to make active
- » Commenting out the parts you want to make inactive

Following are the key settings to check:

- » **TEMP_SENSOR:** This setting usually has more than one value, indicated by `_0` `_1` `_2`, and has a list of types with a number for you to enter from the information. The most common is type 1 (EPCOS 100k). It's essential to match the type being used in your hot-end with one in this list and enter the number for all active hot-ends.
- » **TEMP_SENSOR_BED:** This setting is exactly the same as **TEMP_SENSOR** except that, normally, it uses the same electronics type as your hot-end.
- » **PID settings:** These settings determine the proportional-integral-differential control loop that heats your hot-end correctly to a target temperature that you set in `S1 i c3r`. The settings in the following list indicate to the firmware how your hot-end responds to temperature control signals. Configuring these settings correctly is very important because it alters the stability of temperature control when heating the plastic filament for extrusion. You'll need to use PID values that are designed for the hot-end type you are using; check with the manufacturer for the correct values.
- » The settings you need to change are
 - `DEFAULT_Kp` (proportional element)
 - `DEFAULT_Ki` (integral element)
 - `DEFAULT_Kd` (differential element)



REMEMBER

All these settings may sound complicated, but don't be too worried; using Gcode commands, you can have the electronics provide information about the settings you require. For example, using the `M303` (auto-tune) instruction will provide you with the numbers that the RepRap printer's firmware calculates from doing several test heating and cooling cycles with the machine's hot-end.

Setting the switches

The 3D printer has switches to let the electronics know when the X, Y, and Z carriages are in their home positions. These switches often require an inverted signal (high-to-low signal or inverted low-to-high) that tells the electronics why they're being activated. If your new RepRap machine refuses to move when you set it up, you probably need to change the following settings either to `true` or to `false`:

- » `X_ENDSTOP_INVERTING = true` (or `false`)
- » `Y_ENDSTOP_INVERTING = true` (or `false`)
- » `Z_ENDSTOP_INVERTING = true` (or `false`)

You have to do the same thing with the motor directions if the carriage moves away from your end-stop when you home the machine. Change the motor direction by using the following settings. Do the same with the extruder if it pushes the filament in the wrong direction when you drive it forward.

- » `INVERT_X_DIR = true` (or false)
- » `INVERT_Y_DIR = true` (or false)
- » `INVERT_Z_DIR = true` (or false)
- » `INVERT_E0_DIR = true` (or false)
- » `INVERT_E1_DIR = true` (or false)
- » `INVERT_E2_DIR = true` (or false)

For `X_MAX_POS` and the other axes, you can set a maximum travel distance. This setting is handy if something goes wrong or you accidentally try to print an object bigger than your platform; the firmware stops the axis rather than crashes it into the end of the machine. Movement settings are as follows:

- » `HOMING_FEEDRATE` sets how fast the X, Y, and Z axes move when the home command is executed. If it's set too fast, motors skip and cause machine misalignments.
- » `DEFAULT_AXIS_STEPS_PER_UNIT` is a sequence of numbers, such as `{55.5, 55.5, 500, 200}`. This number sequence relates to the X, Y, and Z axes and to all the extruders fitted to the printer.

Entering this set of numbers correctly is crucial because this setting tells the firmware how many steps each stepper motor must move the axis or filament to move 1mm. If this setting is incorrect, your machine won't produce accurate parts and will under- or over-extrude material. To start, use `200` for the number of extruder steps. Read on to see why this figure is a good starting point — but expect to change it after you complete extruder calibration. The axis movement is determined by the belts and pulleys you've fitted; the kit or machine type gives you that information.

- » `DEFAULT_MAX_FEEDRATE` is the maximum speed at which your 3D printer can safely move while printing without causing skips or motor stalls. An example setting for X, Y, Z, and Extruder is `{300, 300, 300, 25}`.
- » `DEFAULT_MAX_ACCELERATION` defines the fastest rate of change in acceleration, printing, and travel moves. An example setting for X, Y, Z, and Extruder is `{500, 500, 500, 380}`.

- »» `DEFAULT_ACCELERATION` is connected to the maximum setting mentioned earlier in this list and is the starting speed for acceleration. If this setting is too fast, the stepper motors won't have enough time to ramp up to speed, and they'll stall or skip. An example setting is `300` for all motors apart from the extruder.
- »» `DEFAULT_RETRACT_ACCELERATION` is the same as `DEFAULT_ACCELERATION` but is specific for extruder retractions, which have to be fast to effectively stop strings and blobs on your 3D prints. An example setting is `380`.
- »» The `JERK` values are the final movement settings you can alter; they define the safe levels of instantaneous movement of the axis and extruder. It's common for a `Z` axis — which usually consists of threaded rods moving in a nut — to move slowly. Usually, the fastest acceleration of a `Z` axis is still much slower than that of all the other motors. Extruders also require a lot of torque, and to develop torque correctly, they need a low starting point for acceleration. Finally, the `X` and `Y` axes can't move instantly; they need an initial setting (`JERK`) that allows the machine to start moving at a speed compatible with the motors. Typical `JERK` values for a Prusa i3 machine are `XYJERK 20.0`, `ZJERK 0.4`, and `EJERK 12.0`. Values are in mm/second.



TIP

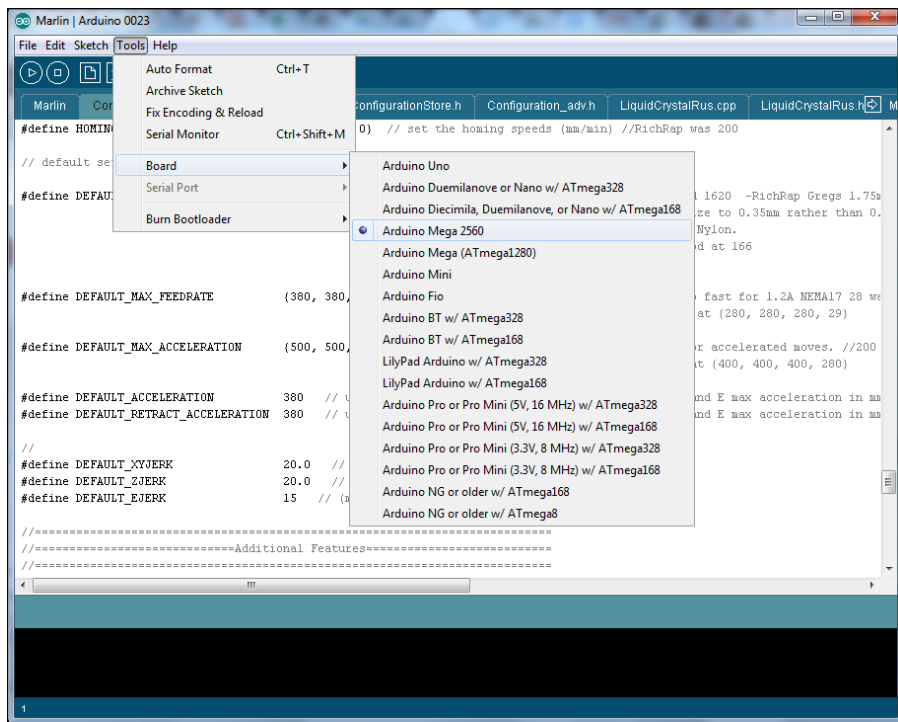
A Delta printer such as the RostockMAX doesn't have a slow `Z` axis, so the `ZJERK` value is the same as the `XYJERK` value.

Uploading Marlin firmware to RAMPS electronics

When you've made your printer-specific setting changes in the `configuration.h` file, save the file, then check to ensure that the following settings are appropriate:

- »» On the Tools and Board tabs, make sure that you've selected the correct Arduino board for your electronics. For RAMPS electronics on the Prusa i3, for example, select Arduino MEGA 1280 or 2560 (depending on the model of the Arduino board that came with your kit; see Figure 13-25).
- »» Select the serial port to which you connected your electronics via the USB cable by choosing Verify/Compile on the Sketch tab. If you have no errors in the electronics connections, you can upload the revised firmware to the electronics via the USB connection.

FIGURE 13-25:
Most RepRap electronics (such as RAMPS) require you to select the Arduino MEGA 1280 or MEGA 2560.



For further details on critical settings for your 3D printer, see Chapter 15. Those settings include calibrations for motion, heating, and extruder flow rate. Some of these settings can often be updated using the desktop 3D printer user control interface, but for other machines, they may expect you to make changes in the configuration files, compile these files, and re-upload them to the electronics.



TIP

I highly recommend *Arduino For Dummies*, by John Nussey (John Wiley & Sons, Inc.). This book is fantastic if you want a deeper understanding of the Arduino programming language and the processes described in this section — especially if you want to modify other parts of the Marlin firmware.

- » Looking at thermoplastic extruders
- » Comparing syringe and paste-based extruders
- » Setting up for multicolor 3D printing
- » Explaining extruder operation and upgrades

Chapter **14**

Understanding, Using, and Servicing 3D Printers

In this chapter, I mostly focus on the 3D printer's thermoplastic extruder and hot-end, since understanding (and learning more about) the process your 3D printer is using to melt and extrude plastic out of a small nozzle are by far the most important things you can do to keep your machine in good working order. Things can get really frustrating when you just don't know why your 3D printer is not performing correctly. Quite often you can trace problems back to extrusion issues. In this chapter, I describe how an extruder operates and show you how to service it. Here, you find advice on keeping everything working well as you print. I also cover alternative materials and explain how you can print with them on your desktop 3D printer. To finish things off, I show you how to perform multicolor printing and even describe some tricks that make it easier to achieve colorful prints of your own.

Examining Thermoplastic Extrusion

The extruder is one of the most important parts of a 3D printer, so the quality and reliability of parts are critical.

You can make all the parts required for an extruder with basic tools and a lot of time, but it's well worth paying for well-machined parts that fit smoothly together and won't leak or melt on you.



REMEMBER

All extruders are required to do the same job: Grip the round plastic filament and drive it in a controlled manner to the hot-end, where it's melted and ejected from the nozzle. The process may sound easy, but when you look at the many parts of an extruder (and, for that matter, of a hot-end), the extruder is the area that causes the most problems for people using home 3D printers.

The filament drive mechanism

Start with the *filament drive* mechanism, which almost always takes the form of a round bolt or rod with concave teeth that grip the plastic filament you've chosen for your project. (See Figure 14-1.)

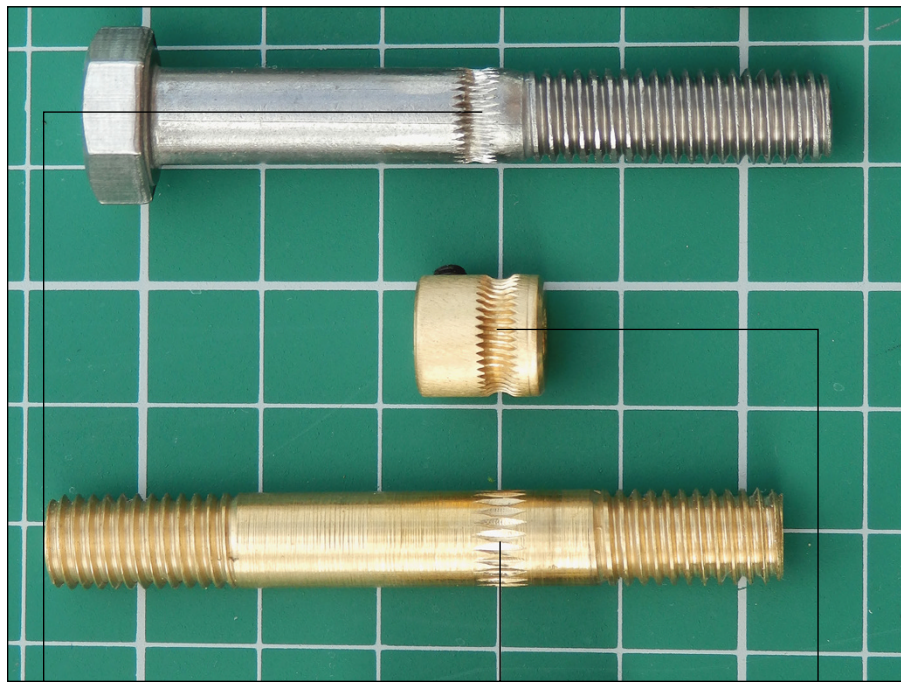


FIGURE 14-1: Typical filament drives used in thermoplastic extruders.

Hobbed-bolt filament drive

Shallow and blunt grooves

Professionally machined drive wheel



Filament drive mechanisms can be machined in a variety of ways. Look for even, well-cut drive teeth that grip but don't strip or grind through your filament. Too-sharp teeth can be as bad as too-blunt teeth.

Filament drives used in thermoplastic extruders perform the same job but are manufactured in various ways. At the top of Figure 14-1 is a traditional *hobbed-bolt* filament drive, which was originally a very common type of filament drive; it performs adequately. In the middle is a professionally machined drive wheel, which usually provides the most grip around the filament as it's pushed into the extruder. This wheel is usually mounted directly on the shaft of the extruder motor or on a gearbox attached to the motor. At the bottom of Figure 14-1 is another machined bar with shallow, blunt grooves; this design won't grip as firmly as either of the top or middle drives shown in Figure 14-1.

You can assemble an extruder in several ways. In the simplest assembly, the filament drive wheel fits directly on the shaft of the extruder's stepper motor and drives the filament directly via rotation of the motor shaft. This method provides the lowest torque but requires the fewest other components.

The most basic filament extruder can perform adequately if you have a powerful drive motor and well-machined hot-end to reduce the forces required to push the filament. On the left side of Figure 14-2 is the same professionally machined drive wheel shown in Figure 14-1 (middle image). On the right side of Figure 14-2 is another direct-drive motor, but with only a basic drive cog with a groove for the filament; it won't have as much grip as the one shown on the left in Figure 14-2. This cog costs little to manufacture but also has the lowest drive performance. A direct-drive motor has no gearing to improve torque, so you should avoid this type if at all possible. Direct-drive extruders do have one advantage: Two of them can be placed close together to provide dual extrusion.

A gearbox can be attached to the output of a stepper motor to greatly improve the torque and rotational resolution compared with the direct-drive extruders I highlight earlier in this section. (See Figure 14-3.) If kept compact, the gearbox can allow for dual extrusion where two independent nozzles can switch between two colors or two different materials.

Many enhancements in extruder drive mechanisms have been developed in recent years. One of the most successful is the dual-grip system, shown in Figure 14-4. The advantage of a dual-grip system is that the round filament is gripped and pushed from both sides instead of being pressed flat on the idler side (which usually squashes it onto a metal rotating bearing). More manufacturers are switching to a dual-drive gear system, which increases grip on softer filaments such as ThermoPlastic Urethane (TPU) rubber and helps drive harder or slippery materials faster.

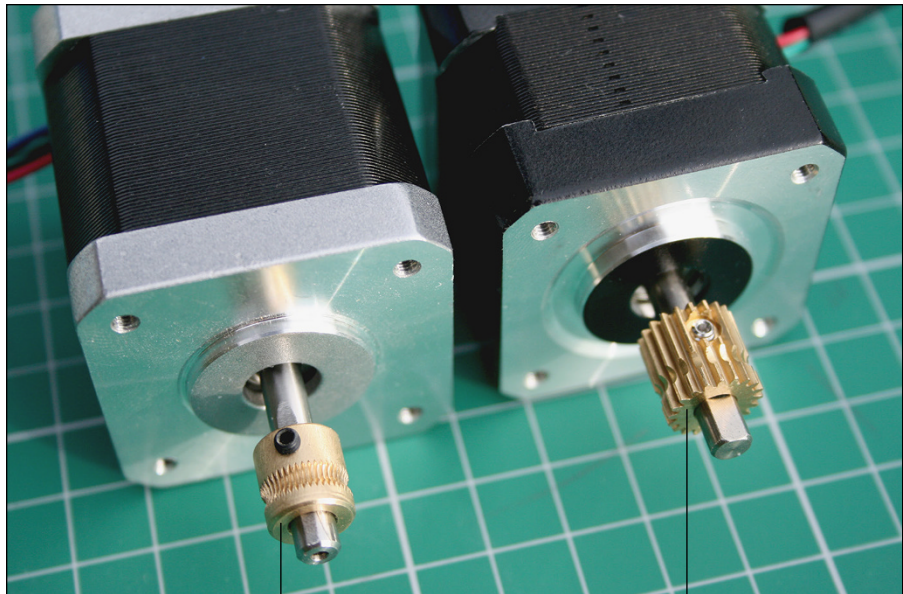


FIGURE 14-2:
Two direct-drive
filament
extruders.

Professionally machined
drive wheel

Machined drive cog

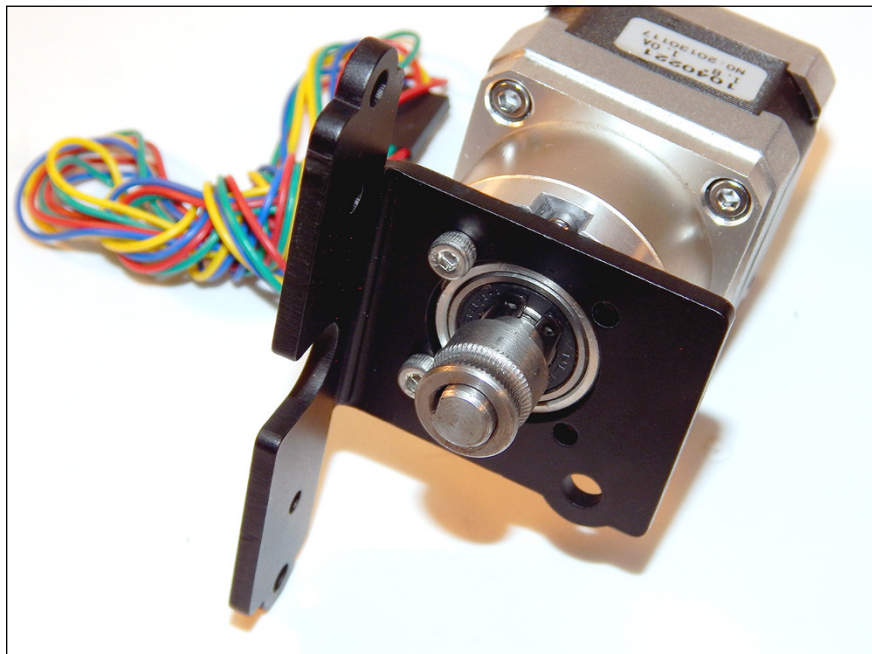
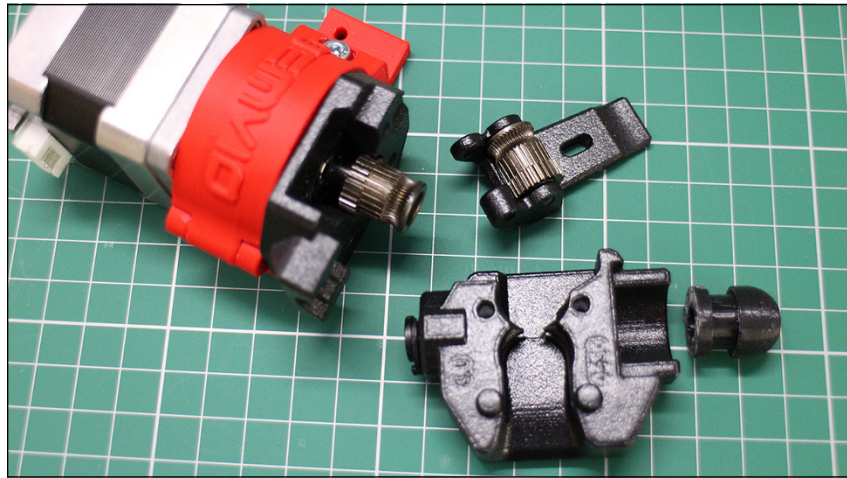


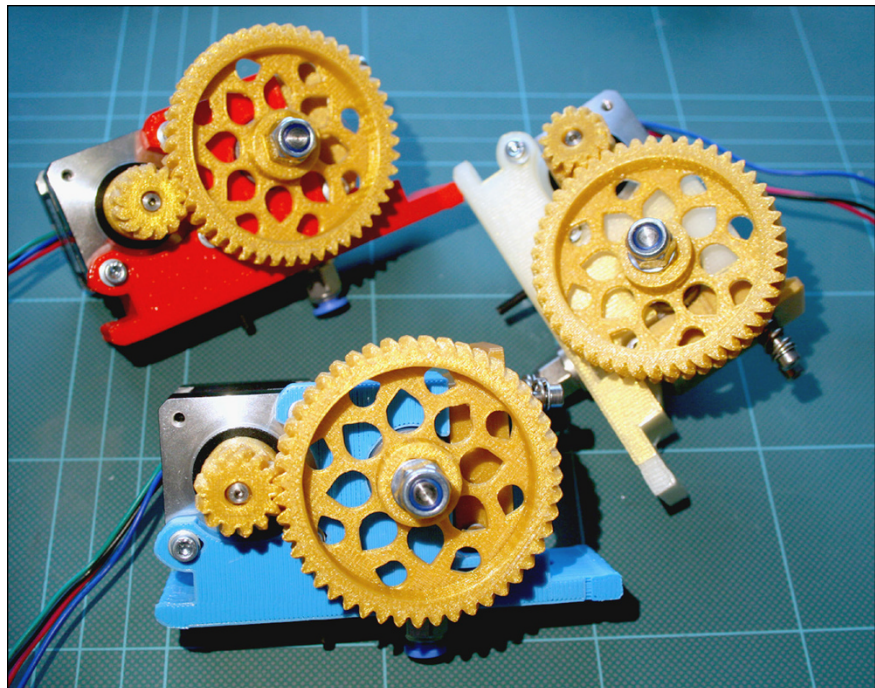
FIGURE 14-3:
A professionally
made gearbox
attaches to the
stepper motor,
improving the
performance of
even small
motors.

FIGURE 14-4:
A Bondtech dual-drive geared extruder mechanism can offer extremely powerful extrusion.



In original and early RepRap 3D printers, it's common for the motor to be connected to a series of 3D-printed gears. (See Figure 14-5.) The gearing allows the motor to turn quickly while the drive mechanism turns slowly, thereby increasing the torque and allowing the filament to be driven with increased force and precision into the hot-end. This arrangement provides fast printing and retraction with less chance of material becoming jammed due to lack of torque.

FIGURE 14-5:
The 3D-printed geared extruder has more parts to assemble but can produce greater power and faster printing.



Another common type of extruder is the Bowden, which works on the same principle as the brake-lever cable of a bicycle. A slippery Teflon (PTFE) tube separates the extruder drive motor from the hot-end. This tube allows the driven filament to be constrained and pushed into the hot-end section.

The Bowden extruder is often used in small or lightweight machines because it offers several advantages:

- » The design removes the bulk, mass, and weight of the motor from the moving carriage, leaving only the hot-end.
- » More hot-ends can be mounted on one 3D printer.
- » The design can be ideal for machines with a lightweight head that moves quickly.

A Bowden extruder does have a few disadvantages:

- » The design has more parts and complexity compared to a non-Bowden design.
- » The printer must perform a longer filament retraction after every print move to minimize oozing due to the pressure and compression spring-effect that occur when the filament is pushed down the tube.
- » The design can be hard to control and tune.

The Bowden extruder shown in Figure 14-6 uses a 1-meter PTFE tube and would be used in a large 3D printer that produces models wider than 500mm.

The idler wheel

Any standard single-grip extruder also needs an idler wheel to push the filament into the teeth of the drive wheel. An *idler wheel* usually is a round bearing pushed by a spring or a rubber bushing. Figure 14-7 shows an idler bearing/wheel fitted to a printed lever; the spring on the left causes the bearing on the right of the image to be pushed into the drive wheel (middle), gripping the filament tightly. With a design using a bearing idler wheel, it must not be overtightened, or it will squash rather than grip the filament. If your extruder uses the dual-drive system, in which teeth grip both sides of the filament, the bearing idler wheel is no longer required, and the filament is unlikely to be squashed.

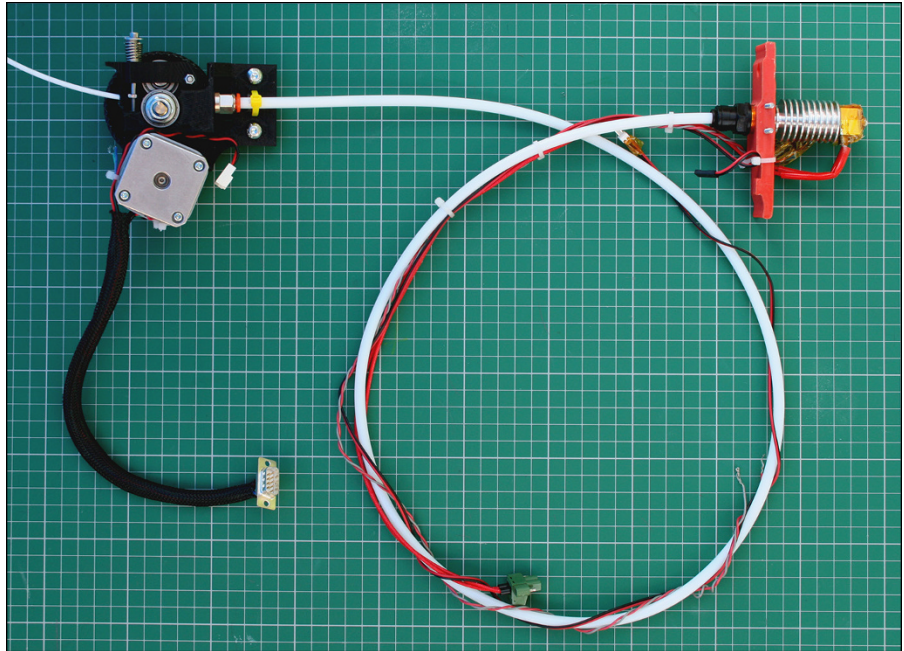


FIGURE 14-6:
A Bowden extruder.

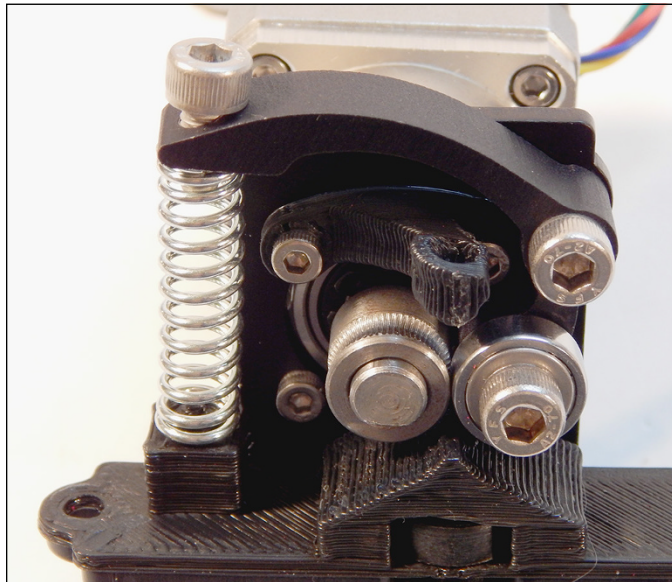


FIGURE 14-7:
The idler wheel is essential and must be tightened just enough for the drive wheel to grip the filament.



WARNING

Don't overtighten the idler bearing. If the grip on the filament starts to squash it out of shape, the extrusion path entering into the hot-end gets harder to force down and it may jam. Check how much the drive wheel is biting into the filament. You should see small, regular marks where the teeth bite in, and the filament shouldn't be crushed.

The hot-end is normally attached to the extruder body with bolts to allow it to be removed if the extruder jams or gets blocked. A finished extruder also requires a heating element on the hot-end, as well as a temperature sensor. (See Figure 14-8.) This wiring, along with the four motor connections, must go back to the control electronics wiring, which I discuss in Chapter 13.

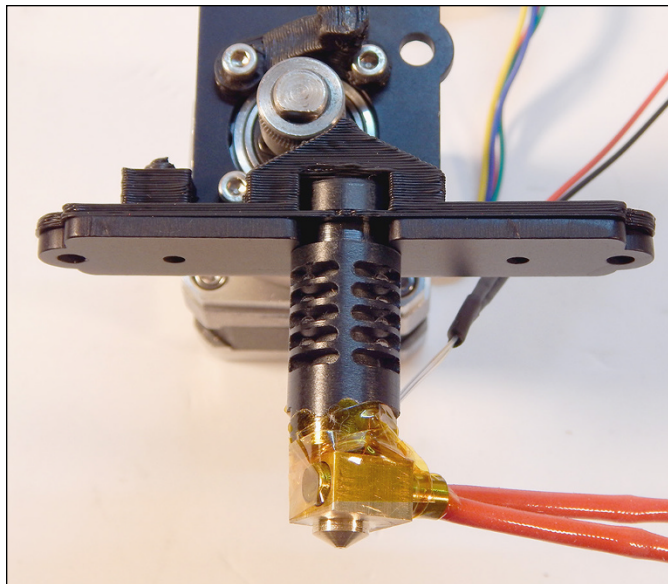


FIGURE 14-8:
A wired-up hot-end fitted to the motor and drive assembly. This figure shows a complete thermoplastic extruder with a machined gearbox.



WARNING

Never try to drive the motor or rotate the gears driving the filament if the hot-end isn't at the correct temperature. Doing so can cause the extruder to strip and chew up the filament, and you have to clean the teeth on your drive wheel before you can print again.



REMEMBER

A thermoplastic extruder needs to be carefully calibrated to operate well; I discuss all the necessary steps to achieve good calibration in Chapter 15. Extruders are highly active subjects of development for RepRap. Many designs exist (see Figure 14-9) — some more specialized than others, offering higher temperature, faster extrusion, or finer detail. Most extruders usually meet the requirements of home 3D printing with thermoplastics.

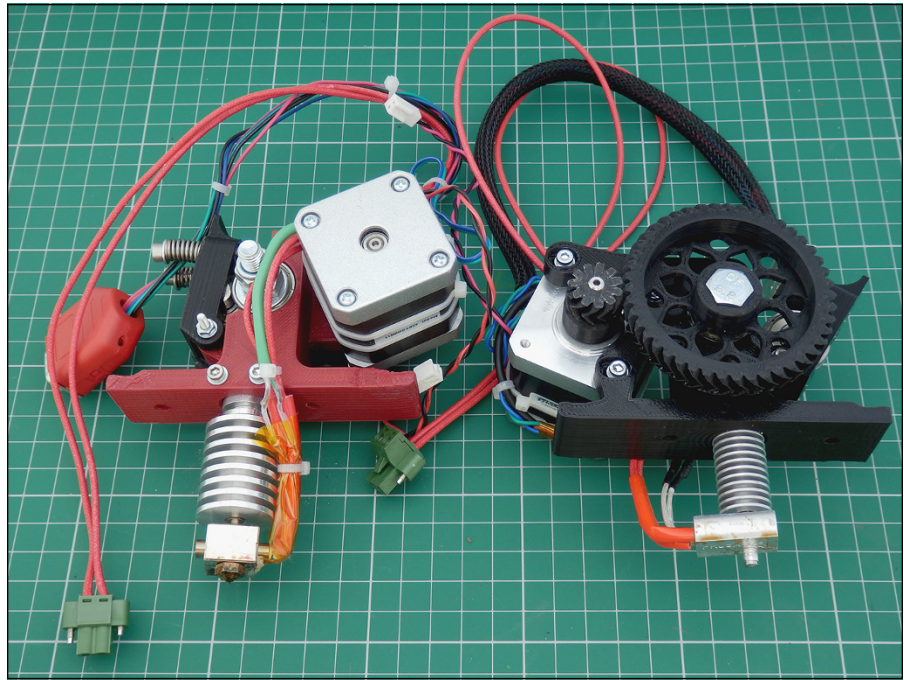


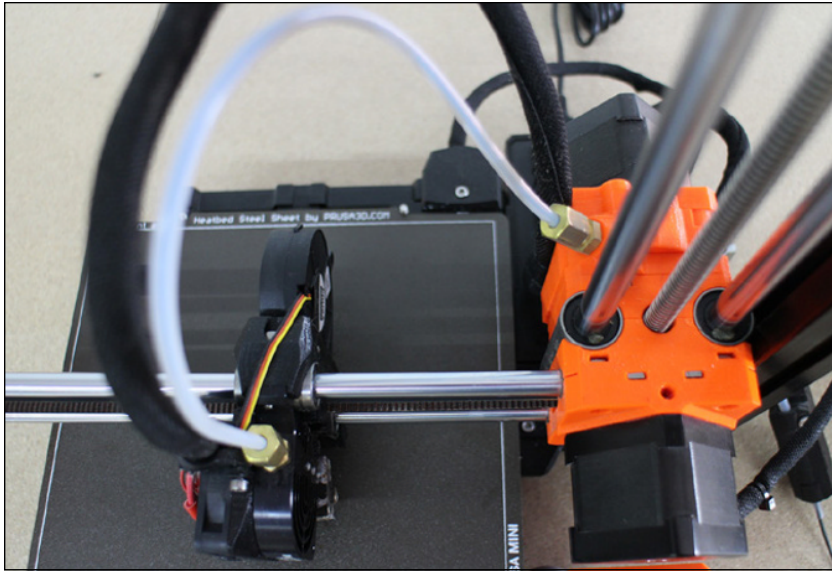
FIGURE 14-9:
RepRap extruder
designs.

Working with the Prusa MINI Bowden Extruder and Hot-End Assembly

In this section, I'm going to highlight the Prusa MINI extruder system and its hot-end assembly. (See Figure 14-10.) I walk you through taking this system apart for service and show you what to look out for if you have problems. Because the Prusa MINI uses a Bowden extruder system — meaning the extruder motor is not located on the carriage with the hot-end nozzle — I will also disassemble a direct drive Prusa i3 MK3 extruder and hot-end system so you can get a feel for that procedure. If you can grasp how these two extrusion systems operate, you'll be ready to tackle almost every type of desktop FDM 3D printer on the market.

The Prusa MINI extruder system uses a remote mounted stepper motor to drive the filament from the spool into a PTFE tube (Bowden tube) toward the hot-end assembly. The PTFE tube constrains the material and the geared filament hobbled drive wheel grips the material and pushes it along the tube at a controlled rate.

FIGURE 14-10:
The Prusa MINI
extruder and
Bowden tube
connected
hot-end
assembly.

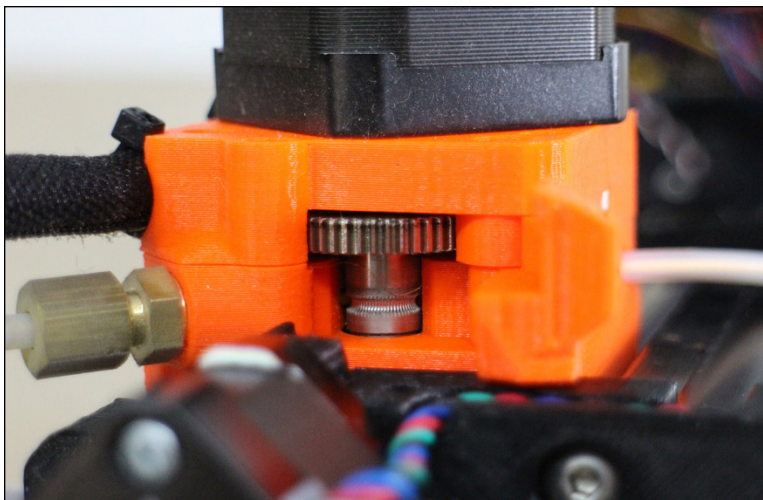


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Disassembling and servicing the Prusa MINI extruder

In most cases you won't need to completely remove the extruder motor or drive gear system; that's usually only necessary if something breaks or becomes loose. Otherwise, the system is designed to be serviced from the latch on the side of the extruder. (See Figure 14-11.)

FIGURE 14-11:
The Prusa MINI
extruder drive
gear access for
servicing and
cleaning.



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For most general extruder gear maintenance, it's easy to lift up the service lever and clean the hobbed drive wheel of any debris blocking the drive teeth as well as any other fluff or dust that may have collected there.

If you need to remove the motor, follow the steps I list below:

1. Eject any filament in the extruder system if that's possible.

The filament may be stuck or, if the filament drive gear is slipping or not operating correctly, you may have to disassemble the extruder without removing the filament. Note you should always heat up the hot-end to the correct temperature before removing filament from the extruder and hot-end system.

2. Let the machine cool down and then turn off the power.

3. Unscrew the PTFE (Bowden tube) clamps from the hot-end and extruder

These should just need to be loosened, and the tube should then pull out.

4. Inspect the PTFE (Bowden tube) for any signs of splitting, melting or excessive wear.

5. Put the tube to one side and unscrew the bolts on the extruder motor holding the extruder gear housing.

6. Unscrew the filament idler bearing to release pressure from the filament drive mechanism.

The motor assembly including the filament drive gear should now be removable from the extruder housing.

7. Check that the drive gear is securely fastened to the motor shaft.

You'll probably need the smallest hex driver (Allen wrench) to tighten the grub screw holding the drive gear to the shaft.

8. Check that the drive gear is clean and has no missing teeth; replace if found to be damaged or worn.

The drive gear will not work correctly with worn or missing drive teeth.

9. Check that the idler is not damaged or deformed and that the pressure bearing runs freely; replace if found to be damaged or sticking in any way.

Most problems with poor or inconsistent extruder drive systems are due to loose parts, worn down gears or drive teeth, or a simple blockage. If you have checked all these points, you can now reassemble the extruder system but don't yet refit the PTFE (Bowden tube) as I am going to show you how to remove and service the hot-end assembly next.

Disassembling and servicing the Prusa MINI hot-end and nozzle

The Prusa MINI hot-end system has an aluminum “cold-end” that is constantly cooled by a fan during printing. This cold-end must stay cool (or at least not hot) at all times. Often when a nozzle jam occurs it is due to a faulty or clogged fan and heat creeping up into the cold-end block, causing the filament to soften, expand, and jam inside the hot-end assembly. Usually, no amount of extruder pushing can release a filament jam like this. Disassembly is sometimes the only option. (See Figure 14-12.)

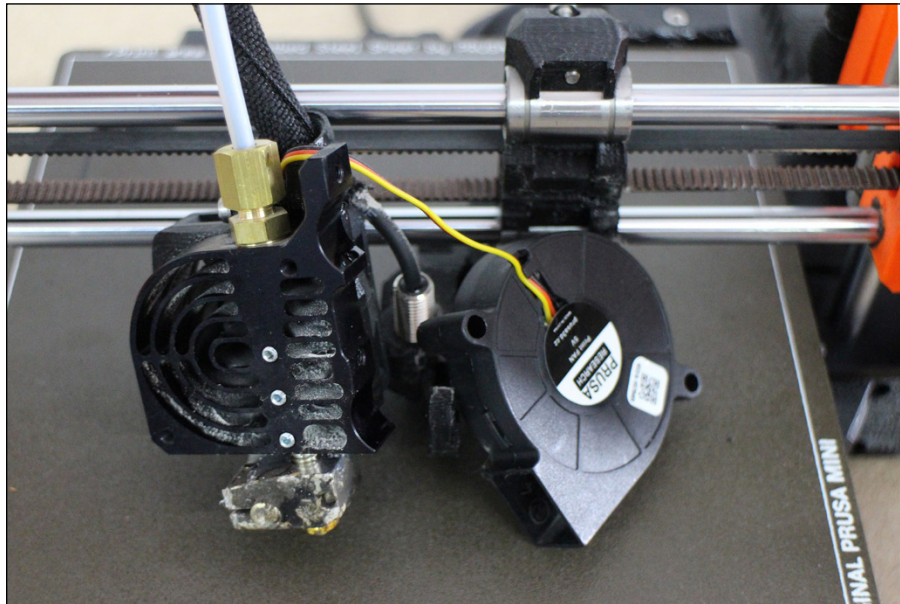


FIGURE 14-12: The Prusa MINI extruder hot-end and cold-end assembly, removed from the printer carriage for servicing.

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One other common cause for jams in your Bowden-fed hot-end comes from partially melted filament remaining behind after extrusion. When you tell your Prusa MINI to eject the filament, it first heats up the material to a point just under normal printing temperatures; then it rams the filament quickly into the nozzle to melt, clear, and form a melted tip. The idea here is for the melted material to be quickly ejected from the nozzle; whatever melted filament left behind gets drawn back down the Bowden tube where it's quickly cooled in the cold-end. By the time the cooled filament gets to the extruder gear, there is no longer any risk of molten material clogging up the hobbled drive gears.

When that all works correctly, you can load material and eject, switch colors, or change the material type before each print. Unfortunately, if for some reason something goes wrong during this process and semi-melted material sits at a point where it could expand and jam around a sealing point (such as the connector for the PTFE tube), you can find that the material is locked in place and the only solution is to disassemble the hot-end, the cold-end, and often the tube used for feeding the material.



REMEMBER

If clearing jams sounds like a real hassle, keep in mind that it is pretty straightforward to remove the cooling fans and allow access to the hot-end and cold end of the printer. The nozzle can also be removed, cleaned, and refitted if required.

To give you an example of the most common issue you may face with a Bowden-tube-fed 3D printer, see Figure 14-13. Here I had to remove two filaments from my Prusa MINI after the extrusion system jammed.



FIGURE 14-13:
An extrusion system jam leaves your filaments damaged.

The filament at the top of Figure 14-13 is a white PLA previously used in the machine. The filament was not the best quality and was prone to snapping if it was left in the machine without being printed for a few days. When the material was ejected, the ramming process to form a plug that could be neatly pulled out was successful, but the filament snapped during this retraction. This was not obvious to me; in fact, a small section of the white material was actually jammed in the cold-end as well as the entrance to the Bowden tube. If you look closely at the picture, you'll see a small ring of material on the top filament; this is where

the material, still partially melted, formed around the ring of the PTFE tube clamp. At this point, the extruder was completely jammed. I then tried to insert a new black PLA material into the extruder, but every time the filament would get all the way to the hot-end it would stop and grind on the filament drive gears, causing the crescent-shaped damage to the filament you can see in the lower part of the Figure 14-13. I spent a lot of time thinking the extruder drive system was not able to push the filament with enough force, so I tightened all the clamps which just made things worse.

In the end, I did finally find the blockage and cleared it, with no lasting damage to the printer. If I hadn't thought things through and discovered the blockage, I could have caused further damage to the extrusion system, the hot-end, and the nozzle.

Examining the Prusa i3 MK3 and Hot-End Assembly

The Prusa MINI Bowden system I describe in the previous section is not the only fish in the sea. Another option is the Prusa i3 MK3 direct drive extruder and hot-end assembly. The two have a lot of similar parts and perform the same function, but both have benefits over the other, and both have their own set of weaknesses.

Disassembling and servicing the Prusa i3 MK3 Extruder

The Prusa i3 MK3 extruder and hot-end system comes as one single part that is directly fixed to the X carriage of the 3D printer. (See Figure 14-14.) The filament feeds directly into the top of the extruder motor and is pushed straight into the cool-end of the heater system. The main downside to a direct drive extrusion system is that all the weight is on the carriage and that can limit the print speed a little. With a Bowden-based system, the heavy extruder motor is mounted remotely so the weight is less, but the extruder *hysteresis* — the delay between an extrusion movement and the output at the nozzle — can be significantly longer, resulting in the need for longer retractions during printing to combat oozing. It's also much easier to print soft filament materials in a direct drive system than in a remote Bowden configuration.

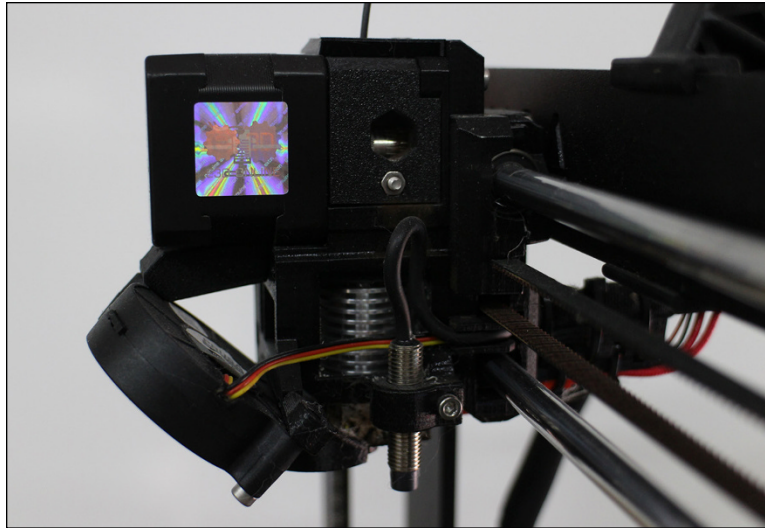


FIGURE 14-14:
The Prusa i3 MK3
combined direct
drive extruder
and hot-end
system.

For the i3 MK2/3/4, you can remove the combined direct drive extruders from the carriage by unscrewing the bolts holding the motor bracket onto the carriage. The process is similar to the steps described in the previous section for the Prusa MINI, but you don't have to bother with Bowden tube feed system, so it's a bit easier:

- 1. Heat up the hot-end to the correct temperature before removing filament from the extruder and hot-end system.**
- 2. Let the machine cool down and turn off the power to the printer.**
- 3. When cool, remove the part cooling fan as well as the extruder cold-end cooling fan.**

Let these fans hang down with their wiring and be careful not to pull on the cables. (See Figure 14-15.)

- 4. Remove the bolts holding the extruder motor onto the X carriage.**

The bolts are of two different lengths, so be sure to keep them straight. Also, make sure that the extruder assembly doesn't fall down as you remove the bolts.)



WARNING



TIP

Note the loom of wires connecting the extrusion system to the main control electronics. You don't have to unclip these; they can stay together in a bunch attached to the back side of the X carriage. You'll still have enough spare wire length to handle the hot-end and bed probe assembly. (See Figure 14-16.)

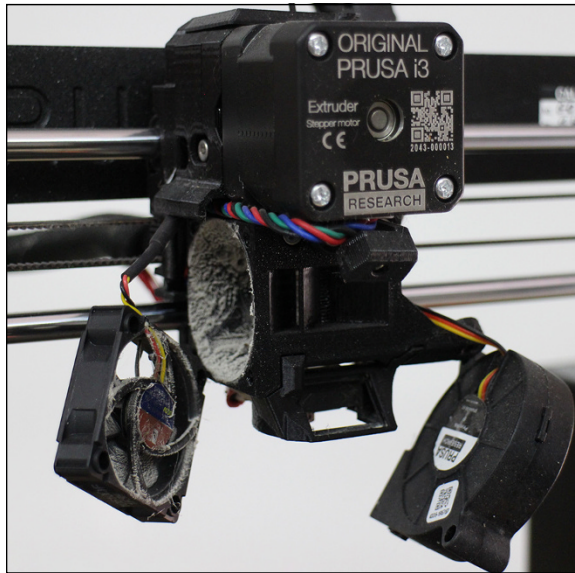


FIGURE 14-15: Unbolt and gently remove both cooling fans.

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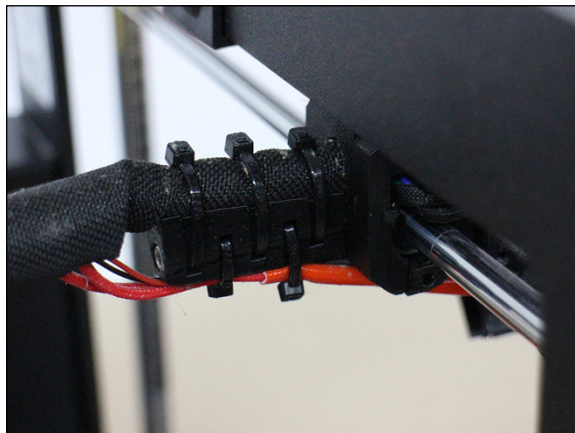


FIGURE 14-16: The wiring loom does not need to be unclipped unless you find a faulty sensor, heater, or fan.

- 5. If you do discover that the hot-end heater is faulty, the thermistor has a problem, or either fan is not working, then you will have to unclip the wiring loom and replace whatever parts are faulty.**

It's common for fans to fail and also for wiring to become brittle and cause intermittent faults, so be prepared to strip this all down at some point and replace one or more of these parts.



REMEMBER

It's very unusual for the bed sensor PINDA probe to fail. It may become loose and not operate correctly until correctly located and tightened, but I have never had one fail on me during use.

6. Finally, check the filament sensor.

Located on the top of the extruder motor, the filament sensor is the last part on this extrusion system having an active element. It has a three wire cable going into the wiring loom back to the electronics control unit. This is another sensor that can fail or get blocked by fluff or debris causing an incorrect detection of filament status and stop a print mid-cycle. (See Figure 14-17.)

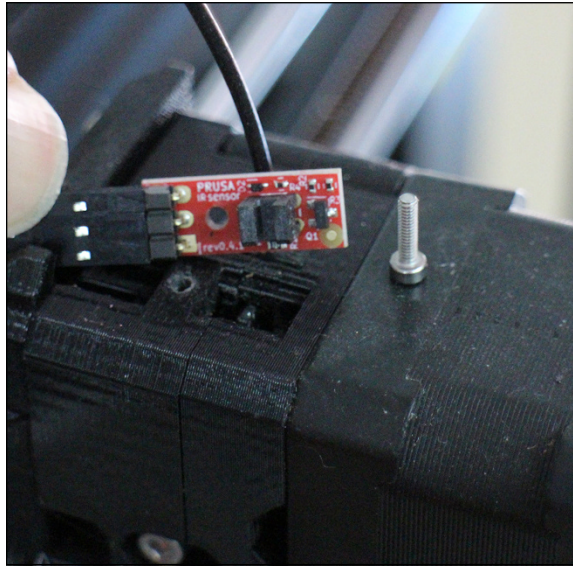


FIGURE 14-17: The Prusa i3 MK3 filament sensor, a tiny printed circuit board with an optical sensor, may need cleaning and checking from time to time.

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Disassembling and servicing the Prusa i3 MK3 hot-end and nozzle

I have already talked a lot about nozzles, heaters, cold-ends, and temperature sensors in this and other chapters. To bring you back up to speed, take a look at Figure 14-18, which shows the hot-end extruder used on the Prusa i3 MK range of 3D printers. It's an open-source design from E3D.

If all you can see is the assembled hot-end system shown in 14-19, you may still be at a loss when it comes to grasping how a hot-end system actually works. So I came up with Figure 14-19, which shows a 3D-printed example of the inside of an all-metal hot-end. This model is great for explaining how a hot-end should be constructed and also when parts need changing or servicing.

FIGURE 14-18:
The E3D V6 all metal hot-end assembly as used in the Prusa i3 MK2 and MK3 3D printers.

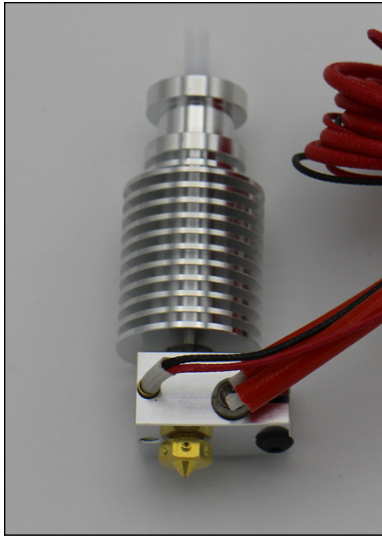
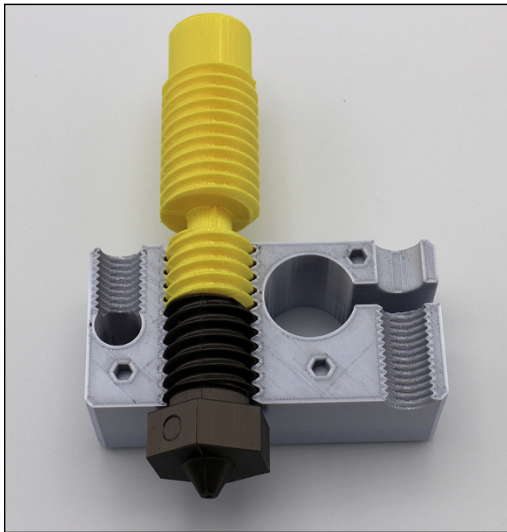


FIGURE 14-19:
A 3D-printed plastic model to help illustrate the E3D V6 all-metal hot-end assembly.



On the left side of the model shown in Figure 14-19, note the hole where a cartridge temperature sensor will be fitted and secured with a small threaded bolt. Next, on the right side of the model, another bigger hole accommodates a powerful cartridge heater (again secured with a longer bolt to clamp the heater in place). The part where the heater and temperature sensor are fitted is an aluminum block that will melt the filament material flowing through the two central threaded tubes. The upper tube is made out of stainless steel; this is the thermal break that separates the hot-end and cold-end parts of the extrusion system. The thermal

break is a stainless steel tube and is designed to be a poor conductor of heat transfer to keep the hot-end hot and the cold-end cooler. The inside surface of the thermal break is polished to a smooth finish to allow the soft filament to flow into the heater nozzle.

The top of the thermal break tube is screwed into another larger aluminum heat sink, allowing a fan to constantly draw away any excess heat from the extrusion system that rises up from the thermal break connection to the heater block. As long as the cold-end stays below the thermal transition point of the material and the hot-end stays at melting point, the filament will melt and flow, and you should not encounter a jam. If one part fails or becomes less efficient — due, perhaps, to a marked increase in the ambient temperature of the room housing your printer — you can start to get extrusion problems. (That’s why I recommend trying to keep 3D printers at a room temperature of [ideally] 25 ° C during printing.)

Lastly, note the nozzle is at the very bottom of the model in Figure 14-19. Its job is to direct the flow of material into a fine hole (typically around 0.4mm in diameter) for extrusion. The nozzle is usually made of brass, but stainless steel, hardened steel, and even ruby-tipped nozzles are all available in the industry standard V6 dimensions of M6 and M7 threaded parts. (The V6 standard is widely used by multiple suppliers to ensure different compatible nozzles can be fitted into various hot-ends and thermoplastic extrusion systems.)

Taking a closer look at the hot-end and the sizes of extrusion nozzles

If you look carefully at the hot-end image in Figure 14-18, you’ll see that the nozzle itself (right there at the bottom of Figure 14-18) has what looks like a dimple on its side. No, it’s not decorative; it’s part of a system that helps indicate what size nozzle is fitted into the hot-end — very handy if you forget or can no longer tell the size due to plastic residue around the end of the nozzle.

This is not some super-secret code, but it’s also not all that well explained by the 3D-printer manufacturers. If you take the official chart from E3D, the following number of dimples explains the exit hole aperture size.

- » Zero dimples = 0.25mm
- » Two dimples on a single face = 0.15mm
- » 1 dimple on a single face = 0.3mm
- » 2 dimples around the face = 0.35mm
- » 3 dimples around the face = 0.4mm

- » 6 dimples around the face = 0.5mm
- » 4 dimples around the face = 0.6mm
- » 5 dimples around the face = 0.8mm



REMEMBER

Many different types of nozzles are available, as shown in Figure 14-20. Be sure to check with your 3D-printer supplier if they use a standard like the E3D V6, Revo, or Volcano. They may have a custom fitting, but ideally aim to select a 3D printer using one of the more standard and compatible systems so you have a good choice of nozzles for different materials and tasks.



FIGURE 14-20: A selection of compatible E3D V6 and Volcano nozzles that can be fitted into the Prusa MINI or i3 MK2/3/4 3D printers.

Comparing fixed nozzle and quick-change systems

So far, I have only discussed nozzles that are considered fixed and, thus, are only occasionally changed for different sizes and types. These V6 style nozzles need to be removed and fitted while the hot-end is at printing temperature. If they are fitted when the hot-end is cold, there would be a small gap due to expansion as the system is heated. Having to exchange nozzle ends when hot is not ideal and is one of the most hazardous aspects of FD-based desktop 3D printers. Therefore, a number of manufacturers such as E3D have started making quick-change combined nozzle and heat-breaks (E3D Revo) that can be changed for different types and sizes more easily and more quickly. Another way to provide some level of flexibility is to use a multi-nozzle system or a combined nozzle, but these are very uncommon. (Figure 14-21 shows one example.)

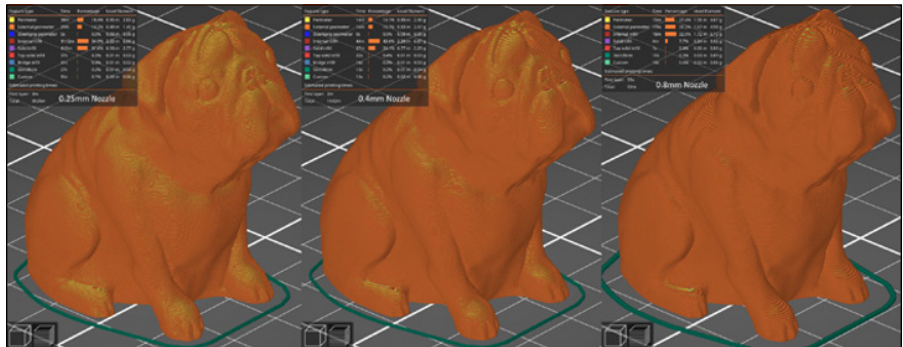
FIGURE 14-21:
The three-way diamond nozzle and triple extruder feed system lets you print using multiple colors.



Nozzle sizes for different print jobs

Over the years of desktop 3D printer evolution and development, the standard optimal nozzle size has settled into being 0.4mm in diameter. It's a very common size of nozzle for a new 3D printer, good for those detailed smaller prints as well as bigger models when you don't want the print job to take forever. But why not change to a nozzle size for better details? Or faster printing? In this section I go through some of the pros and cons of using nozzles of different sizes. As a practical example of why you may decide to change your nozzle size, check out Figure 14-22. This small model of a pug is only around 40mm tall and has small details on the surface. Selecting a small 0.25mm nozzle will give the most detailed print and a layer height of 0.15mm. Unfortunately, using this 0.25mm nozzle will make the total print time 3 hours and 25 minutes.

FIGURE 14-22:
The same model sliced for a standard 0.4mm nozzle, a 0.25mm nozzle, and an 0.8mm nozzle.



If you were to use a standard 0.4mm nozzle, the details are almost all still captured with the output print and the layer height is a little higher at 0.2mm, but the overall print time is reduced to only 1 hour 42 minutes.

Lastly, if you go for an 0.8mm nozzle, the model will not be as detailed and the 0.3mm layer height will be more obvious in the final output print, but the model will be adequate for many situations, and the total print time is now only 55 minutes.

For detailed jewelry (model figures with fine surface textures and smaller parts), the 0.25mm nozzle or even smaller is going to be a good choice. But it will take plenty of time to finish. Larger sizes — 0.6mm and 0.8mm, with 1.0mm and 1.2mm also possible on some machines — will give a very large deposition rate of material extrusion, so the print time will be drastically reduced, but the model detail will not always be replicated into the final model print. These bigger nozzles are absolutely ideal for functional print models such as enclosures, brackets, and any parts that need strength over detail. Big nozzles can provide stronger models and faster print times.



TIP

If you don't want to keep switching nozzles, it's a good idea to have a machine dedicated to a specific size nozzle. The Prusa MINI, for example, is a smaller machine with a reduced build area, but that's often ideal for printing tiny detailed models and a 0.25mm nozzle, or the standard 0.4mm size will provide a good balance of quality and print time.

Bigger machines don't need to have a large nozzle fitted, but if you are attempting to print something around 300mm × 300mm × 300mm in size, it's likely to take many days to a week to finish using a 0.25mm nozzle. Even a standard 0.4mm will still likely be several days of printing and that's not ideal at all.

These are the reasons why I went with a standard desktop 3D printer with a build area of around 250mm × 200mm × 200mm and using the standard 0.4mm sized nozzle as the highlighted machine in this book. Later in Chapter 15 I go over some of the other ways you can speed up printing without too many compromises in terms of quality.

Alternative Extrusion Systems for Paste and Edible Materials

Syringe and paste-based extrusion systems aren't widely used in desktop 3D printers, but they can provide a vast range of applications if you replace your thermoplastic-based extrusion system with a cartridge deposition extruder. You

can print using a syringe-based extruder system on many desktop 3D printers, and some machines can only print using soft materials like clay, chocolate, and even pancake batter.

In the early days of home 3D printing, the Fab@Home project (<https://en.wikipedia.org/wiki/Fab%40Home#History>) chose to develop open-source printers by using various pastes instead of thermoplastics. RepRap has been a little slow to adopt paste materials for printing, but they can be ideal for some purposes.

I have a particular interest in syringe-based 3D printing. When trying this process on my own early RepRap 3D printers, I discovered that controlling the material was difficult. Many early attempts at paste extrusion used compressed air to force the material out of the syringe, often without controlling the stop and start of the flow. When the object began printing, it had to keep going until the end, which was fine for printing (say) a flat cookie or a spiral vase but that didn't allow for real 3D printing.

I set out to equip my 3D printer with an extruder that could be used and controlled in much the same way as a traditional thermoplastic extruder. After a few models and a flash of inspiration, I ended up with a design for a universal paste extruder. (See Figure 14-23.) Instead of using compressed air, my design uses a normal stepper motor to drive a timing belt that mechanically pulls down a syringe plunger, extruding paste materials onto the build platform layer by layer. This design was released as an open-source project, and before long, people all over the world were using it, developing variations on the design, adapting it for different uses, and fitting it to all manner of machines. That's how open-source technology is supposed to work.

The universal paste extruder is easy to use on any RepRap machine as well as many of the open-source 3D printers around today because, as far as the control electronics go, the stepper motor performs the same job as a thermoplastic extruder. To work this bit of magic, you need only recalibrate the number of steps that the motor requires to extrude a set amount of material. With a paste extruder in place, you can experiment with all sorts of materials. (See Figure 14-24.) My favorite materials are clays and ceramics. After all, if you make a mess with them, you can scrape them off your build platform, add a little more water (if required), and try again.



TIP

When using paste materials, it's a good idea to fix a sheet of grease-proof paper or aluminum foil to your platform to keep materials like clay from drying too fast. It also makes removing things like clay much easier.

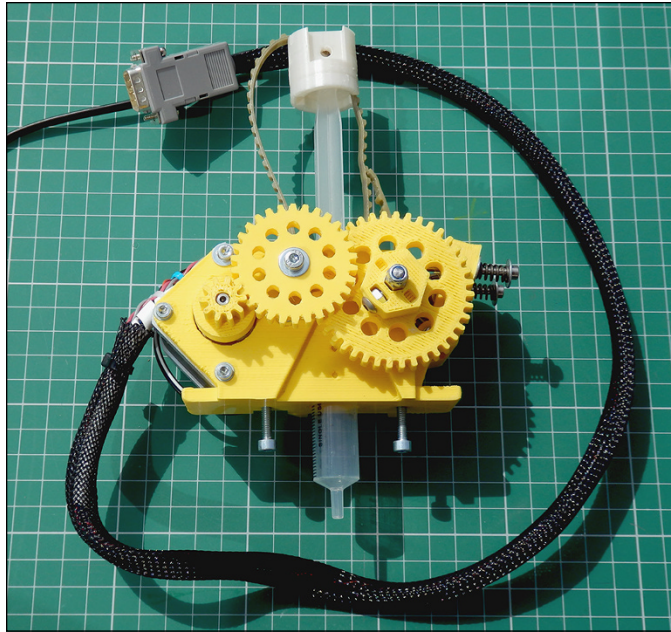


FIGURE 14-23:
The universal
paste extruder.

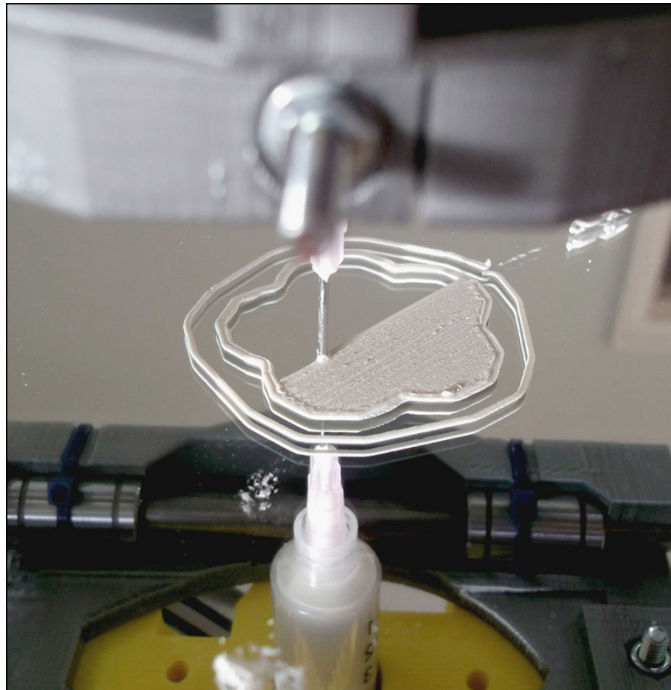


FIGURE 14-24:
The universal
paste extruder
printing porcelain
clay on a mirror-
glass surface.
Note the syringe
fitted to the
extruder; a fine
nozzle layers
the clay.

Precious-metal clays and other ceramic materials can be extruded directly into 3D models or jewelry in this way. (You'd need a plastic 3D print in combination with the lost-wax process to achieve a similar result with other systems.) When the parts are dry, some can be fired or finished by hand as needed.

In addition to clay-based materials, you can print with gels, various types of silicon sealants, and many foods (including sugar paste, heated chocolate, marzipan, and frosting) if you can get a smooth-enough paste to form. People have even experimented with various batter mixes that 3D-print directly over a hot frying pan for custom waffles and pancakes. (See Figure 14-25.)



FIGURE 14-25: Printing chocolate muffin mix requires a basic syringe without a needle, which provides a 3mm bead of extrusion.

Pastas and fondants make for great food-based 3D-printing experiments. Masa flour (used to make corn chips) is a perfect food for 3D printing: It sticks to itself, and after it's extruded onto a baking tray or silicon sheet, you can bake it for the ultimate custom-designed crunchy treat.



TIP

If you want to print your own universal paste extruder, you can get the full build instructions and download the 3D model parts to print at <https://www.youmagine.com/designs/universal-paste-extruder-for-3d-printers>.

Multicolor Print Methods

So here's a question often asked by users wanting to 3D-print models at home: Is it possible to print objects in many colors and even mix, on demand, the color of your choice from a set of five or six master materials? While it is true that full-color home 3D printing is still a little way into the future, you can still use several methods to brighten your 3D-printed objects right now. In this section, I introduce you to multi-extruder printing and color mixing while also showing you how to achieve impressive results with a single extruder.

Looking at the toothpaste effect

In one of the many RepRap experiments conducted at Bath University in the United Kingdom, Myles Corbett and Dr. Adrian Bowyer investigated mixing two colors in a single nozzle. They discovered that plastic materials don't blend naturally; instead, they produce a "toothpaste effect," similar to striped toothpaste. (See Figure 14-26.) Corbett and Bowyer continued to develop the extruder. After trying all sorts of baffles, chambers, and passive methods of achieving a mix, they concluded that only an active method of stirring the melted plastic together *inside* the hot-end would provide true mixed-color output. They did this — and it worked.

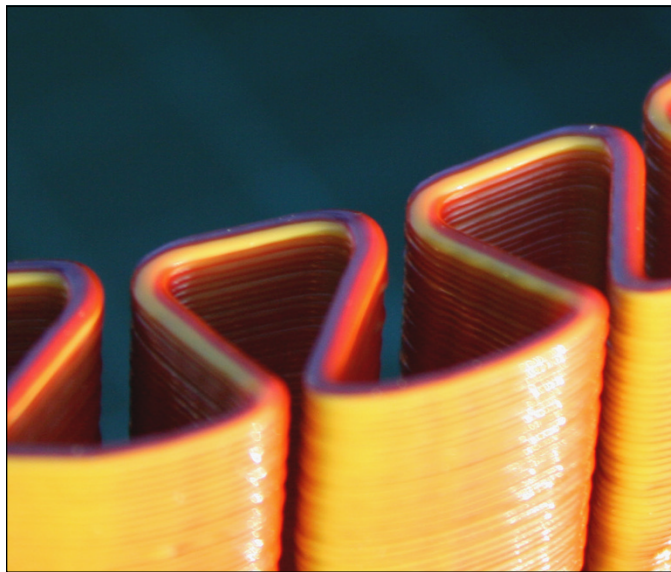


FIGURE 14-26: The toothpaste effect occurs when multiple colored materials are fed into a single hot-end.

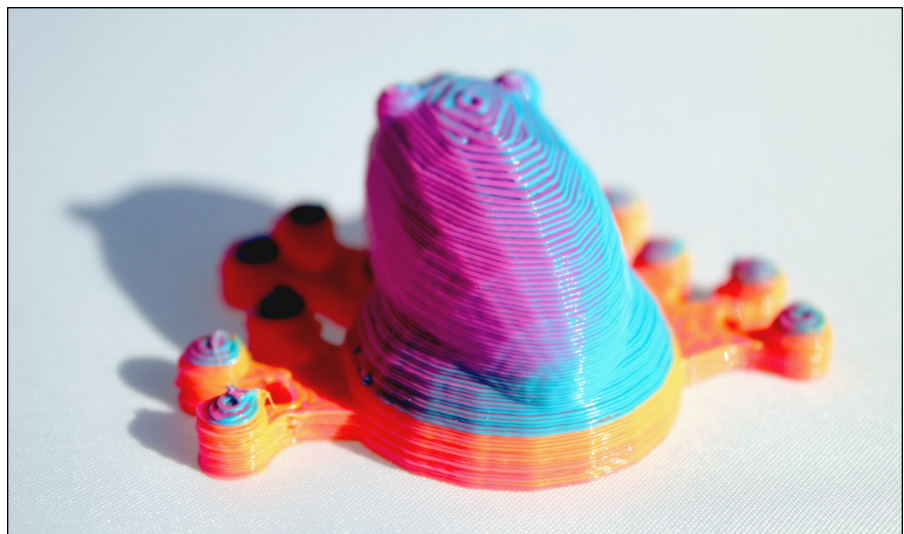


If you'd like to read more about Corbett and Bowyer's work, you can find an excellent report on color mixing at Bath (more than 50 MB of it) at www.reprap.org/mediawiki/images/0/05/RepRapColourMixingReport-jmc.pdf.

Three-way color mixing

My experiments with color and material mixing led to the creation of a three-way extruder that feeds three materials into a single nozzle. I found that each extruder could be controlled and that the toothpaste effect could be interesting, so I decided to pass on an active mixing system. This approach produced unique prints, with different colors appearing on two or three sides of an object. (See Figure 14-27.)

FIGURE 14-27: A three-way blending nozzle combines cyan, magenta, and yellow feeds to produce a psychedelic printed frog that changes color when viewed from different angles.



Further details on this approach to three-way color mixing are available at <https://richrap.blogspot.com/2012/08/3-way-quick-fit-extruder-and-colour.html>.

Two-color printing

A common way to produce a two-color print is to use two separate extruders and two hot-ends. (See Figure 14-28.) You can load one color into the first extruder and a different color into the second. For that matter, you could load different

types of materials if you find that they'll print together. The slightly more complex process, which uses thermoplastic, involves these general stages:

1. Design two 3D objects that fit together and load them into your slicing software.
2. Specify a different extruder for each printed object and combine the Gcode output into a single Gcode file that the printer understands.
3. The 3D printer heats both extruders. While it prints the first object with Extruder 1, it drops the second extruder's temperature enough to keep the plastic from oozing out.
4. The printer lowers Extruder 1's temperature, and Extruder 2 prints the first layer of the second model.
5. The printer repeats the process until both models are printed, fused as one object in two colors.

In Figure 14-28, the dragon and heart are separate 3D objects, placed together in the slicing software. One extruder is specified for each object, and each extruder is fitted with a different-color filament. (I discuss using multiple extruders in detail in Chapter 15.)

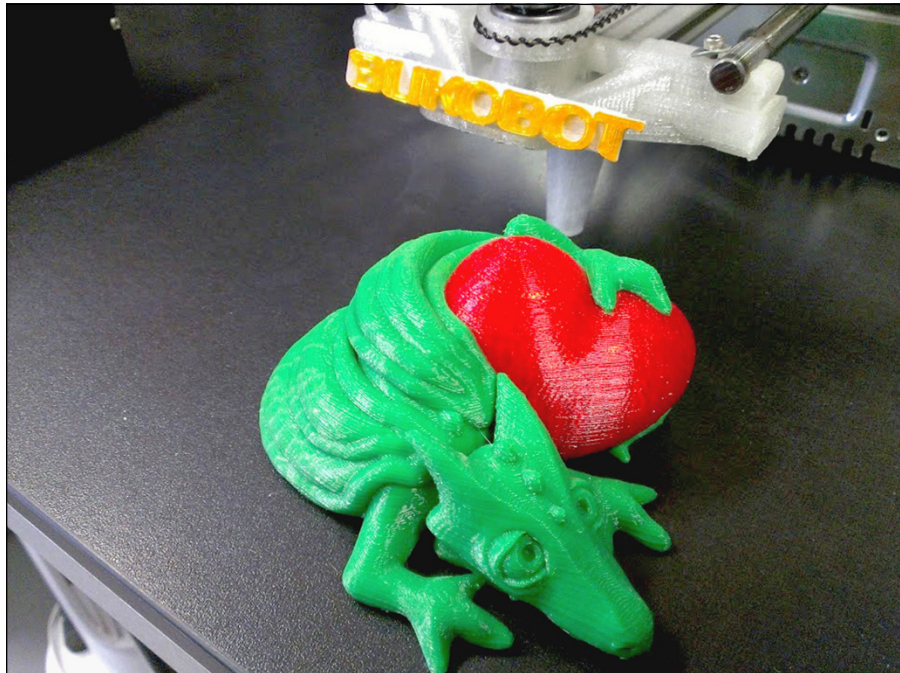


FIGURE 14-28:
A dual-extruder
print.

Photo courtesy of Rich Cameron

Layer-selective color printing

What if you have only one extruder but want to try some multicolor prints? You can achieve impressive, colorful results on almost any RepRap 3D printer by using a process called layer-selective color printing.

When I first started 3D printing, I wanted to be able to use multiple colors of a filament on a single print process. To make that happen, I designed a simple filament joiner. This approach allowed sections of different filaments to be melted together; when the fused filament line was used in a 3D printer, it made objects with stripes of different colors.

You can 3D-print a wide range of useful objects using different colored layers. For example, signs allow a colored background to be printed first and a different color of text to be added on subsequent printed layers. Either joining filament strands together or switching filament color during a 3D print allows production of many separate colors by designing the object's features with different layer heights and printing different-colored layers on top of each part. For example, the flag shown in Figure 14-29 was designed with the red, white, and blue features at slightly different heights; when one color finished printing, another color printed on top of it. Selecting the parts of specific layers to expose produces a multicolored object.



FIGURE 14-29: Layer-selective color printing with a single extruder involves using different layer heights.

Cut-and-follow-on printing

A simpler method doesn't go for the joining-the-filaments approach of layer-selective color printing, but rather uses a two-stage cut-and-follow-on process, as follows:

1. Carefully cut the filament close to the extruder while an object is being printed.
2. Feed another color manually as the extruder draws down the cut end.

With a little patience and practice, you can use this technique to produce all sorts of interesting color effects.

The only downside to this approach is that the filament oozes during printing. With a normal, solid length of filament, the extruder retracts a little after each print move. But with cut-and-follow-on printing, the extruder retracts while a section of cut filament isn't joined to the preceding section, meaning a little filament oozes out of the hot-end. Moving the printer carriage very quickly can compensate for the ooze, but such fast moves weren't possible in the early days of home printing due to heavy motors and bulky extrusion systems; in general, filament joining was a better solution.

If you print an entire plate of many parts and if you can cut and load a new color every 15 minutes or so (or however often you desire), you could end up with an entire set of printed parts in fabulous colors. Figure 14-30 shows a set of 3D-printer parts that were printed in rainbow colors with a single extruder using the cut-and-follow-on method for continuous printing.

Multi-input feeder

For a more sophisticated and automatic color or material change system, a set of multiple extruders called the MMU (Multi Material Upgrade) is also available for the Prusa i3 MK3/4 machines. This upgrade allows multiple color or different materials types to be loaded at the same time; a selection gearbox will then automatically pull, switch, cut, and feed each required filament as the model prints. This process can take an extremely long time to produce a print, but the benefit is that you are not limited to only vertical color changes; you can have any change of color or material type at any position in the model. For example, a living hinge made out of soft rubber can be printed in-place when a jewelry box is also being made from multiple color filaments. The completed hinged box will come off the printer, and no further processing or assembly is needed.

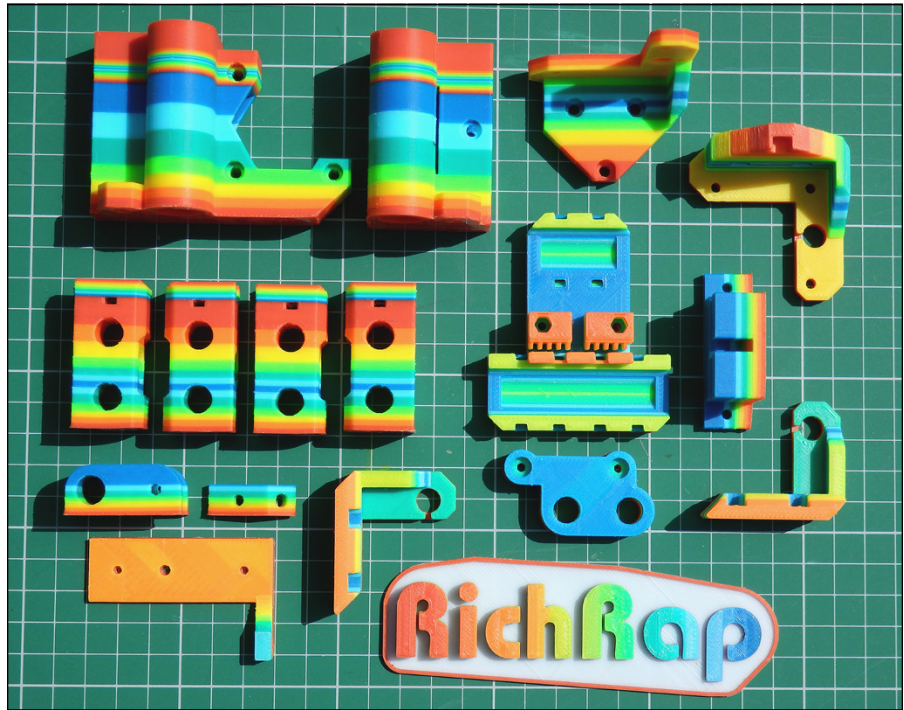


FIGURE 14-30:
Continuous multicolor printing via the cut-and-follow-on method.

AN ALTERNATIVE METHOD FOR SWAPPING FILAMENTS



TIP

If you're not feeling confident enough to use the cut-and-follow-on method, most 3D-printing software interfaces (such as Pronterface) allow you to pause a print so that you can make changes. Just follow these general steps:

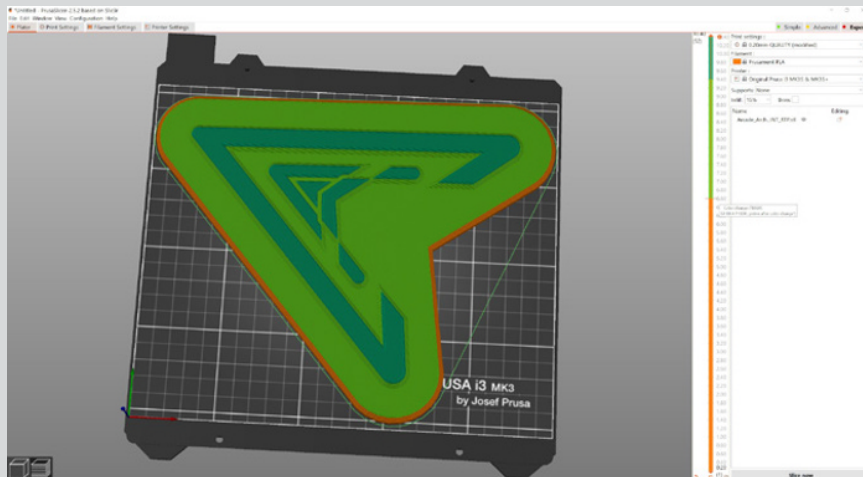
1. Pause, but don't stop, the print process.
2. Manually release the extruder idler.
3. Pull out the color filament just used.
4. Replace the filament with a filament of another color.

(continued)

5. Don't push down too hard; you don't want a blob.
6. Tighten the extruder idler again and continue the print.
7. Check that the extruder continues to feed filament; if not, pause and check the idler.

This approach works the same way as the cut-and-follow-on method; it just takes a little longer. Most slicing programs now also allow you to automatically select and insert pause and filament change points anywhere in the Z-axis (vertical) print.

If a 3D model of a building sign is designed so features on the sign are at different heights, the face of the sign could be printed in white and at the point of printing text or a logo on the top surface of the face, the 3D printer will pause and eject the filament. Then all you need to do is insert another color and continue the print and then repeat with as many color or material changes as you require. (See the figure below.)



The completed and printed building sign can be seen in the second figure below. This process does require manual changes of filament colors or materials by the operator, but as an occasional process it's a very effective form of multiple color 3D printing using only a single extruder system.



Automatic tool-changers

The next step up from an additional MMU is to either invest in a dedicated multi-tool head-based 3D printer or even go for a tool-changing machine. These types of 3D printer are now coming to the desktop market. They are significantly more expensive and complex to operate, let alone the fact that a multicolor or multi-material 3D model must be designed for them to be used. (I predict that multi-tool head and tool-changing machines will continue to be developed and eventually modular 3D print heads will be commonplace in most 3D printers; see Figures 14-31 and 14-32).

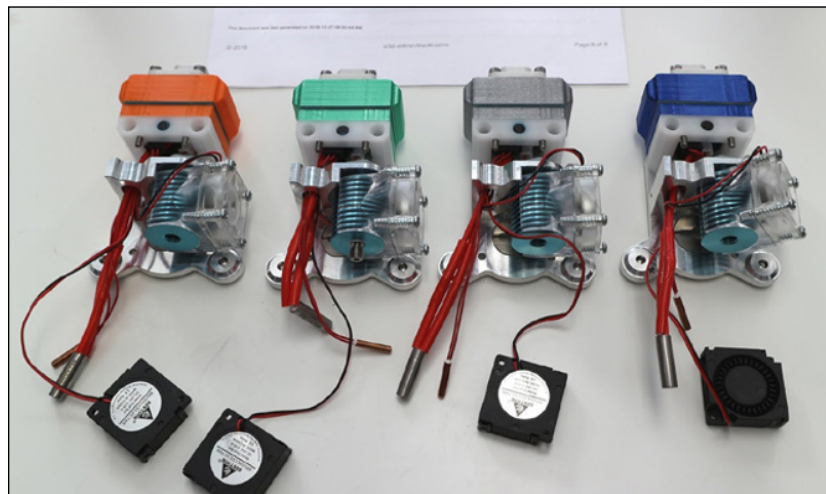
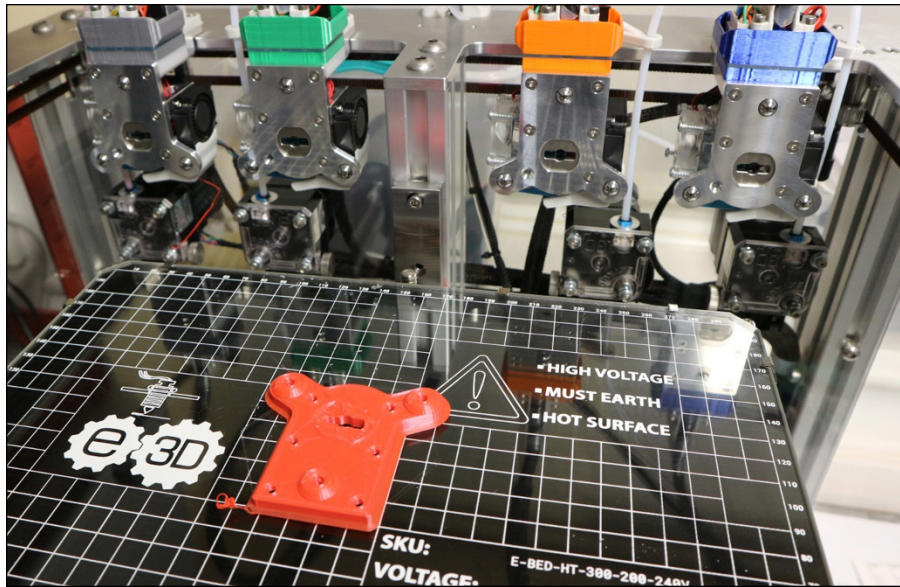


FIGURE 14-31: Four modular automatic tool-change 3D print heads from an E3D tool-changer system.

FIGURE 14-32:
The E3D
tool-changer
system allows
four print heads
to be switched
during a 3D print.



Extruder Operation and Upgrades

In this section, I present you with a whole host of tips to keep your extruder and 3D printer happy. Keeping your extruder in tip-top condition is important because the extruder is the device subjected to the most wear and tear in your 3D printer. Follow this advice to make your 3D printing go smoothly, prevent failed prints, and keep your new 3D printer in action:

- » **Check the accuracy of your software and firmware.** Always make sure that the temperatures reported by your firmware and software are accurate. This check can resolve a lot of common problems and extend the life of your 3D printer.

You can check the temperature in several ways. One of the best methods is to insert a thermocouple probe into the hot-end nozzle. Or, you could invest in a noncontact digital laser temperature sensor, which sells for around \$30. (See Figure 14-33.) To use it, point the laser at the place you want to measure. This device is good for checking the temperature of the heated print bed, motors, and drive electronics.

- » **Verify the temperature of your cold-end.** It's a great idea to check how hot the cold-end (thermal barrier) is getting on your hot-end. As I discuss in Chapter 11, the cold-end's temperature needs to stay below the glass-transition

temperature of the material you're printing. This limit is most critical for printing polylactic acid (PLA) materials, so check your extruder when it has been turned on and printing for 20 minutes or so. If the extruder heats up more than 50 ° C, consider adding a cooling fan. Make sure that this fan points across the cold-end part of the extruder, not toward the hot-end or the object being printed.



TIP

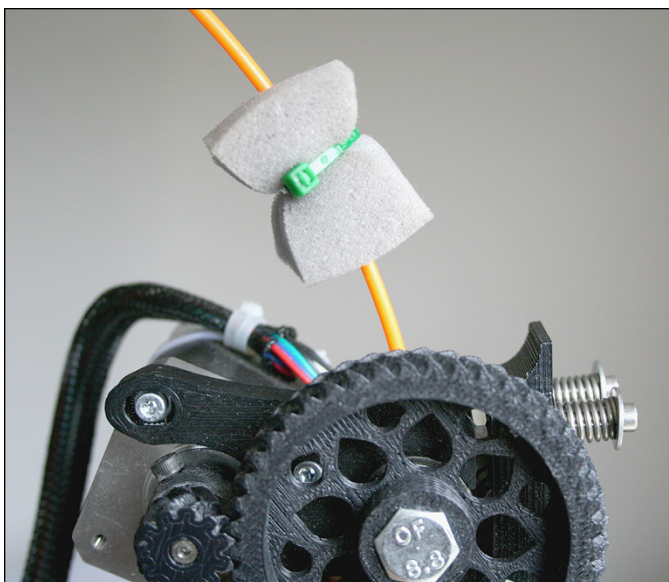
Some 3D-printer kits come with a fan to cool the cold-end of the extruder — usually, a very good idea. A fan isn't always necessary, but having your incoming filament go quickly from cool to melting temperature is much better than trying to push a plug of heated, semisoft, rubberlike material into your extruder nozzle.

- » **Keep your filament free of fluff.** Add a fluff-capturing device to your 3D printer, because dust and fluff on the filament going into your hot-end can clog it and eventually jam the nozzle. Such gunk is very hard to clear out. A piece of sponge, secured around the filament with a zip tie, catches fluff and stops it from entering your extruder. (See Figure 14-34.)



FIGURE 14-33: Use a noncontact laser temperature sensor to make sure that the parts of your 3D printer are running at the correct temperatures.

FIGURE 14-34: A piece of dry sponge keeps fluff, grease, and dust from entering (and jamming) the tiny nozzle of your hot-end.



Fixing a blocked hot-end or extruder

When your hot-end gets blocked or your extruder's filament drive fails, the warning signs are usually obvious. The stream of plastic starts to lessen and then stops; the printer keeps trying to print but extrudes layer after layer of nothing.

The first steps to take are to stop the printer and ensure that the heater block on the hot-end is still at the expected temperature. (Ideally, for maximum safety, you should use a noncontact laser temperature sensor, as discussed earlier in this section.) If the heater temperature is significantly below 160 °C, the heater used in the hot-end or temperature sensor may have failed or the wiring or electronics controlling the heaters may have developed a problem.



TIP

Unfortunately, wires commonly break — and insulation wears away — on a home 3D printer due to the constant movement of the machine. Wiring should always have plenty of room to move around gently, with enough slack — not tightly bent or yanked back and forth as the machine moves. Using silicon-coated wire can help, especially if it has extra resistance to heat. Increasingly, new machines use gently curved *ribbon cable* — a ribbon of many parallel wires instead of a single thick wire — which tends to alleviate cable strain and damage.



WARNING

Always take care when working on the heated extrusion system. Keep in mind that at some point it's going to be necessary to do repairs and fix jammed nozzles when the nozzle is at full temperature or at several hundred degrees C. Using a modular or quick-change system can reduce the need to work on your machine when it's still hot.

If your heater block is jammed but is at the expected temperature, follow these general steps to clear the jam:

- 1. Keep the heater block turned on.**
- 2. Make sure that the filament drive isn't blocked and that the filament isn't buckled or wrapped around the extruder drive wheel.**

If you think you may have a blockage, follow the steps here. If you have buckled filament wrapped around the drive wheel, first remove the buckled filament and then follow the next steps to check whether the cause of the buckle was a blockage.

- 3. Release the idler bearing and gently pull out the filament.**

A filament rarely gets so jammed that it can't be pulled out while the hot-end is at temperature. More commonly, the removed filament shows signs of being overly compressed — a little fatter where it melted inside the hot-end. Usually, pulling out the melted filament removes contaminants from the hot-end nozzle.

- 4. Cut off the melted part of the filament end and then push the remaining filament into the hot-end.**

If you're able to push down and material is extruded from the nozzle, you've cleared the blockage. Otherwise, proceed to Step 5.

- 5. If you can't get the material to extrude, allow the end of the material to melt and pull it out again.**

Repeating this step several times should clear most blockages. If not, proceed to Step 6.

- 6. If you still have a blockage, do either of the following things (extremely carefully):**

- Push a pin or small drill bit into the nozzle end while pulling out the melted filament.
- Allow the hot-end to cool, and when it's cool, use a chemical solvent (such as acetone) to dissolve any buildup.



WARNING

Before using any chemical cleaner, check with the supplier and mention the type of material that you were using in the hot-end when the jam occurred.



TIP

You may be starting to think that having a few extruders is a good idea — and usually, it is. In the event of a blockage, a backup extruder can get you printing again while you repair. Another reason for having a choice of extruders is that your machine becomes much more capable of printing different types of objects, which can widen your selection of available printing materials.

Acquiring an assortment of extruders

For thermoplastic printing, it's a good idea to have two or more extruders of the same type but with different nozzle sizes and maybe a choice of 2.85mm or 1.75mm filament. Some materials — especially soft or experimental materials — may come in 2.85mm and less often in 1.75mm. Depending on the manufacturer, 2.85mm filament may cost less than 1.75mm filament.

Having a choice of nozzle sizes is great if you intend to print parts of varying quality. Although you can always print with a small nozzle, the print job may take a lot longer for certain parts. Using a bigger nozzle can be handy if you want to create rough drafts of your models or intend to finish the resulting object with paints or fillers.



TIP

A good all-around nozzle size is 0.4mm, which allows for fine detail and a reasonable print time for most parts. You can also select layer heights of 0.3mm or lower.

This isn't to say that a big nozzle can't provide high quality. You can select very low layer heights if you're using a big nozzle, which makes the vertical quality of a print almost identical to what you'd get with a small nozzle, though some fine horizontal details may be lost if the model has many sharp corners and features. Think of a 3D-printing nozzle as being similar to a paintbrush. You can use a small brush or nozzle for finer details and sharper edges; a big brush or nozzle "paints" faster but can't resolve intricate details clearly.

A typical large nozzle for a home 3D printer is 0.6mm or 0.8mm. A 0.6mm nozzle allows you to print layers of 0.5mm or lower and usually gives you a much faster print time than smaller nozzles. Some large RepRap printers use 1.2mm nozzles to produce models a meter (or more) tall or wide in size.



TIP

Don't set a layer height that exceeds the size of the nozzle. Keep the layer smaller than the nozzle to ensure good bonding of plastic layer on layer. For a 0.4mm nozzle, your maximum layer height should be no more than 0.35mm. If you select 0.4mm layers, then you will have very poor layer-bonding in the final model and usually a failed print process.



TECHNICAL
STUFF

You can try using as small a nozzle as your machine mechanics allow. Keep in mind, however, that normal minimum layer heights are around 0.1mm (100 microns) — about the thickness of a sheet of office paper. Most Desktop 3D printers allow layers of 0.05mm (50 microns) and even smaller, but printing time increases dramatically, and the extra quality is hard to distinguish. Common layer heights are 0.2mm or 0.25mm, which produce a highly presentable surface. As you become more accustomed to 3D printing and tune your printer to run faster, you'll find pleasing resolution at layer heights around 0.15mm or 0.1mm.

If you decide to keep more than one extruder available for your 3D printer, you don't need to fit all the extruders on your machine at the same time. In many situations, having a quick-fit mechanism that allows you to change extruders easily makes sense.

I was frustrated with early RepRap machines not having a simple way to switch out extruder systems. At the time, all extruders were mounted permanently on the moving X-axis carriage with nuts and bolts. Changing extruders was both time-consuming and tricky, and users couldn't even think about having more than one type of extruder.

I developed a quick-fit carriage and various extruder bases for the most common hot-ends and paste extruders. The idea was to allow experimentation and make extruders easy to change and lock into place on RepRap printers. (See Figure 14-35.)

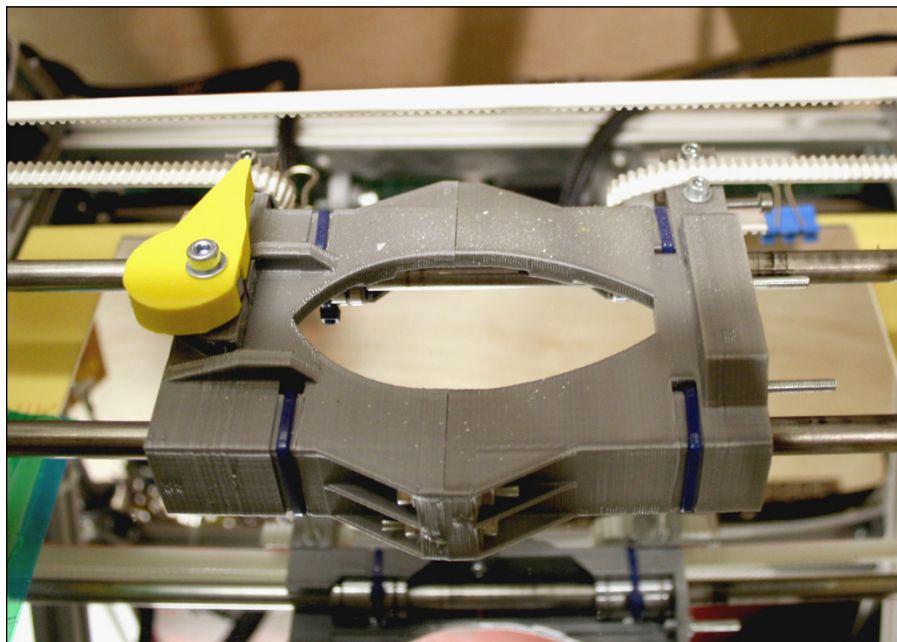


FIGURE 14-35:
A replacement X carriage compatible with many RepRap 3D printers. The lever at left allows the quick fitting and removal of extruders.

Cooling extruders with fans

Here's a final tip for using 3D printing extruders: Use fans. In the "Extruder Operation and Upgrades" section, earlier in this chapter, I discuss using a small fan to keep the cold-end insulator of your hot-end below the glass-transition point of

your plastic. When you start experimenting with printing ultra-tiny objects with fine details or printing objects at great speed, you quickly discover an interesting problem in 3D-printing thermoplastic materials: controlling layer temperature.

If you print tiny parts that have little layer surface area or turn out objects at such high speeds that each layer is completed in a matter of seconds, the layer of plastic just laid down doesn't have time to cool, so it's still a little molten when the next layer is laid down. With the radiated heat from the nozzle and more hot plastic being extruded, the model can end up being a messy blob instead of the object you intended. You can slow the speed, but you may not resolve the problem; you shouldn't have to wait even longer to print an object anyway. In this situation, a controlled cooling fan can make a massive difference.

The cooling fan is usually around 80mm wide and is controlled by the printer's electronics. In your Slic3r-generated Gcode, you can specify how fast a cooling fan runs as well as when the fan turns on and off. When your printer has a cooling fan fitted, Slic3r can run the print at full speed, even when printing fine details of a model. When your printer doesn't have a fan, Slic3r has to instruct the Gcode to slow to allow natural cooling of the plastic before adding more. As you can imagine, fine structures can be tricky to print without a cooling fan.

I discuss setting up the fan in Chapter 15. In this section, I point out that a fan permits bridging of extruded material — an essential part of many 3D-printed objects. *Bridging* occurs when a model has to span a gap, essentially making a bridge in thin air. If you extrude plastic with nothing below it, the extruded material naturally sags and sometimes breaks. Although you can bridge filament without using a fan, you usually have some strings of snapped extruded filament hanging down, as well as a little sagging. When you use a fan to cool the plastic as it's extruded, you can make a tight bridge and get smart-looking results. (See Figure 14-36.)



TIP

Mount the fan so that it cools the top layer of the part being printed. If you cool the heated bed, your part will pop off in the middle of the print. If you accidentally cool the hot-end, your extruder may jam. It's quite common for a cooling fan to have a 3D-printed duct that directs a stream of air across the printed object while it prints, to minimize unwanted cooling of the heated bed and hot-end. (See Figure 14-37.)



TIP

In almost all cases, it's not advisable to use a cooling fan when printing acrylonitrile butadiene styrene (ABS) material. The fan may cool the edges of the material too fast and cause them to curl; the next layer may be worse. Eventually, the part can be so deformed and warped that the print head may knock it off the build platform. By contrast, PLA likes a fan.

FIGURE 14-36: Bridging a filament. With good cooling and a few alternating layers, the spanned first layer becomes a solid surface that can be printed on after a second bridging layer is laid down in the opposite direction.

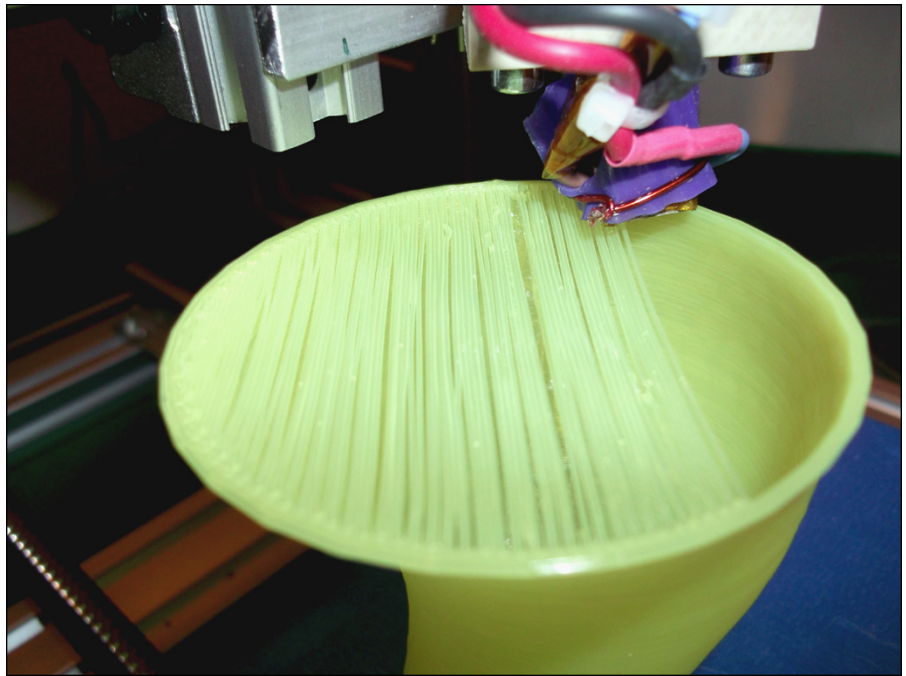
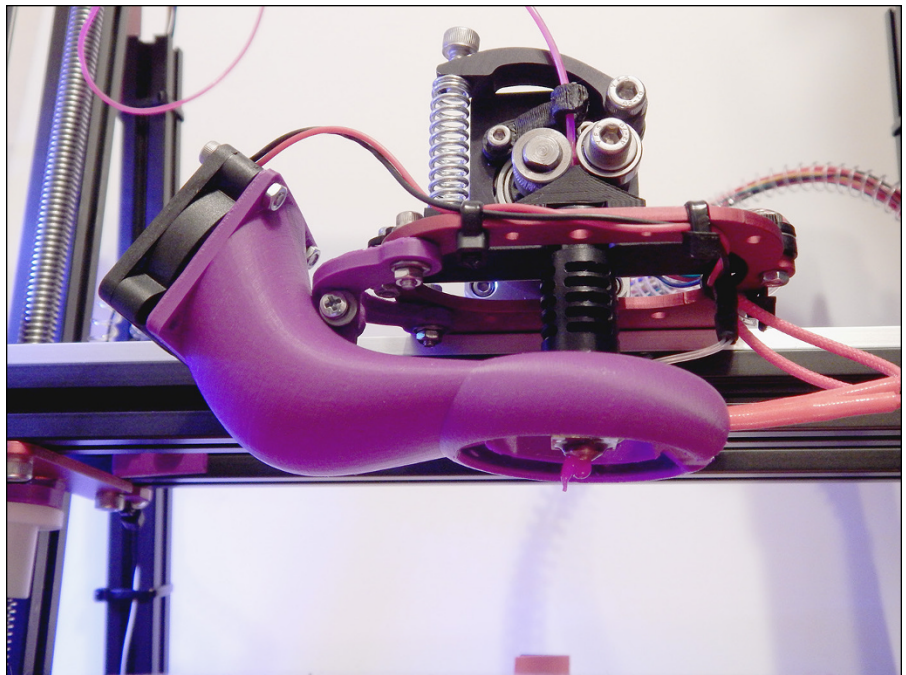


FIGURE 14-37: A printed duct cools the part being printed and doesn't accidentally cool the hot-end heater.



- » Locating 3D design software and models
- » Preparing, slicing, and selecting settings for models
- » Calibrating your 3D-printing machine
- » Creating your first 3D-printed objects

Chapter **15**

Identifying Software and Calibrating Your 3D Printer

This chapter covers the final phases of desktop 3D printer setup: print processing, calibration, and determining the slicing settings for your 3D model files. I also discuss the best ways to print models, the various sources of 3D models, and common 3D-modeling packages. I go into some detail about preparing your model files and producing output Gcode (with Prusaslicer), which you can then use with your desktop 3D printer. Before getting into the nuances of printing parts, I show you how to make sure that your machine is calibrated and ready to print your first object. Finally, I have you look at some common types of 3D objects and how to use specific settings and machine configurations to achieve the best 3D-printed results.

Finding 3D Design Software and Models

The entire 3D-printing process starts with the design of a 3D model. In this section, I walk you through some of the steps you need to understand in order to successfully print 3D models. It is far from a click-and-print process. You need to have the correct model format and have chosen settings that will process that model within the limitations of the 3D-printing process.

Objects designed for home 3D printing can be ready-made models you can use straight away. Usually, the designers of these objects have home 3D printing in mind when they come up with their designs, expecting that their models will be 3D-printed before any modeling process starts. After all, if you start to understand the limitations of the 3D-printing process, you'll have a clearer goal when you start making your own models.



REMEMBER

The promise of home 3D printing doesn't mean that you can print anything and everything. This practical limitation can frustrate users who expect to jump right in and start printing high-quality parts for product development or model-making, or as substitutes for products crafted by hand or manufactured traditionally.

In fact, 3D printers are good at producing objects that *can't* be made by other manufacturing techniques. Figure 15-1 shows two such examples. Most users, however, don't need to create such complex models — at least, not for their first projects. Most home users of 3D printing face the more standard problem of simply getting what they need out of a 3D printer.

As an example, if you wanted to print a model of a person for a scale-model railroad, you might want that person to be in a seated position with arms stretched out. (See Figure 15-2.) Software packages such as Poser (www.posersoftware.com/) and Trimble's SketchUp (www.sketchup.com) make this sort of modeling easy to do. A 3D-printing bureau that uses a professional selective laser sintering (SLS) 3D printer would have no problem printing this model. Printing it yourself on a home 3D printer, however — especially as an ambitious early project — can be a real challenge.

The main difficulty for fused filament fabrication (FFF) desktop 3D printers is that they can't extrude into free air; the object must be supported while the printing is going on. Each new layer needs a supporting layer to build on. In printing a model of a seated person, then, the feet and lower legs print just fine, but the 90-degree overhang of the upper legs and the outstretched arms present a problem: The extruded filament has nothing to attach to. With nowhere to go, the filament collapses into a mess of extruded spaghetti.

FIGURE 15-1: Two 3D-printed objects that would be impossible to produce on injection-molding machines.

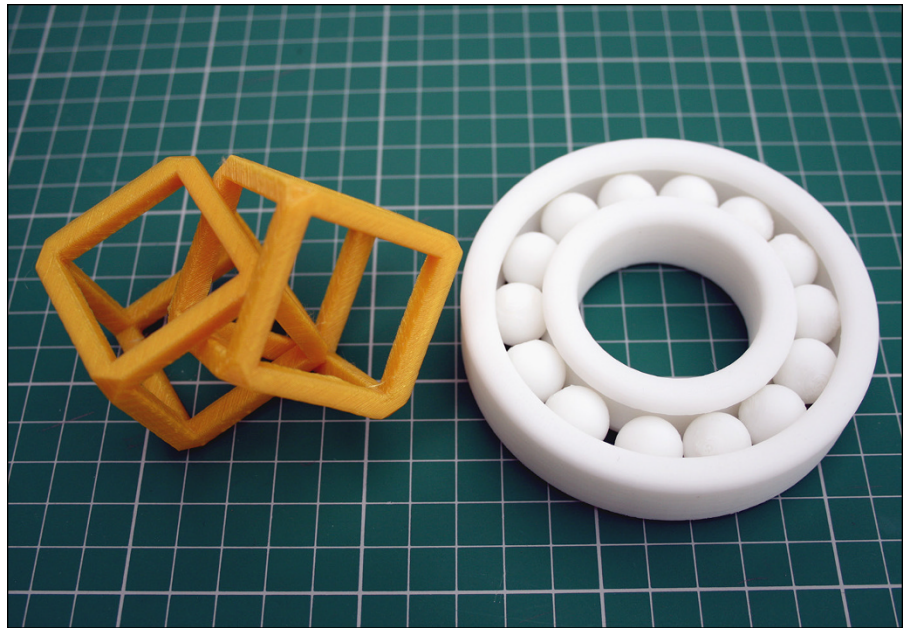
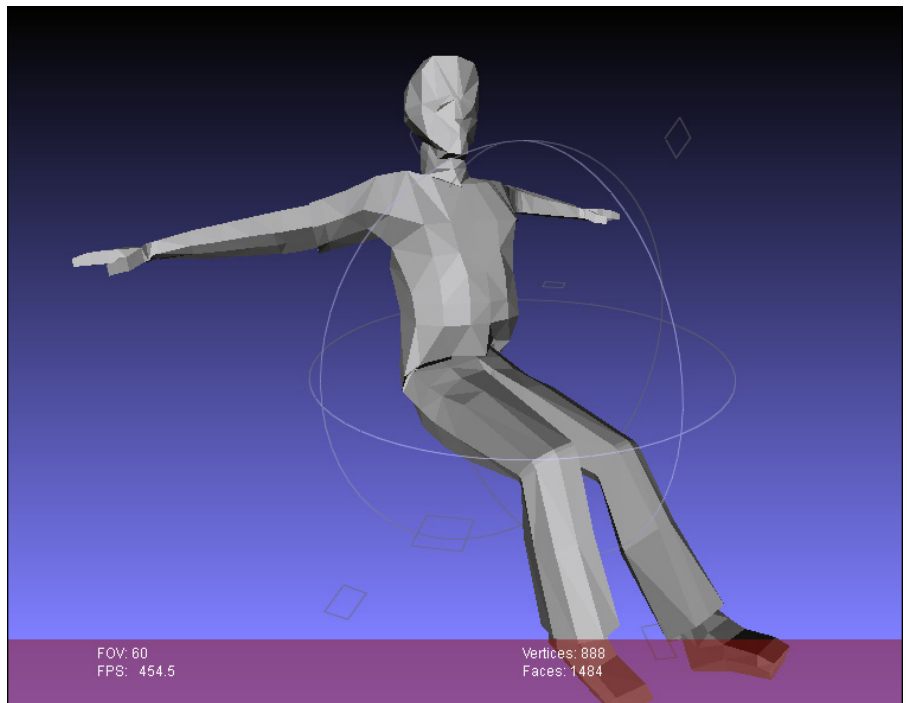


FIGURE 15-2: A posed person is a challenge to print on a home 3D printer; the model has overhangs where the printed material would lack support.



A professional SLS 3D printer works differently: It builds objects by using fine nylon powder. A laser melts the nylon layer and fuses the shape of the object; then another complete layer of fine powder is spread over the build surface, and the process repeats. The main difference is that all that spare unfused powder provides support for the fused parts as they build; the parts that eventually extend from the model into free air can be built with support from the unfused powder and stay in place while being printed. When the model cools and the excess powder is brushed off, the model is complete. Models printed this way can be almost any shape and complexity. That process isn't possible with home 3D printers — at least, not yet.

To help with this problem, you can use a support structure that builds a fine column of material from the base of the bed (or from the printed part itself) to support any overhanging features. The Prusaslicer software (discussed in the next section) can detect where to add support. You can even use a second extruder to put a different support material in the build.



TIP

Normally, home 3D printers use the same material for the model as for the support material. All the extra material has to be snapped off and the model cleaned up a little when the print is complete. (See Figure 15-3.) Prusaslicer model processing software can add support material automatically wherever it's required.

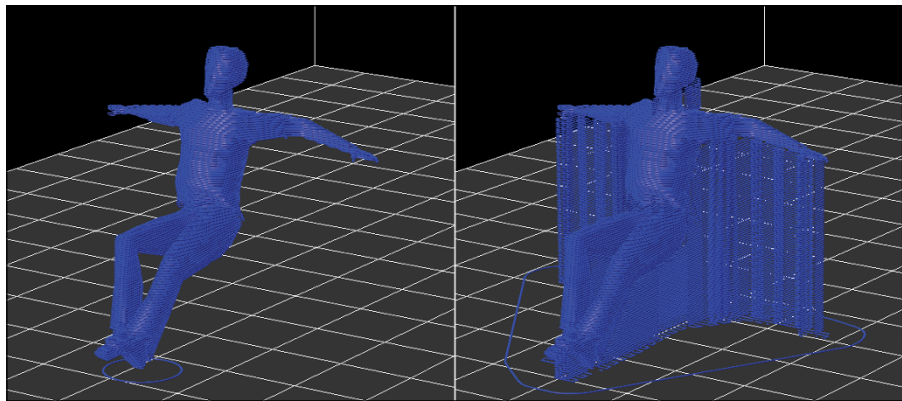


FIGURE 15-3: The unprintable model (left) and the same model with breakaway support material (right).

Basic model

Basic model with support material added



REMEMBER

Adding support material does the job, but keep in mind that the support material is temporary and must be cut away when the print is finished. This cutting can leave marks and scarring. If the printed parts are intricate, removing the support by hand can be difficult. (See Figures 15-4 and 15-5.) Using a second extruder to provide a more workable support material — say, a thermoplastic such as

polyvinyl alcohol (PVA) — allows you to trim the object by submerging it in warm water. The PVA dissolves, revealing the finished model. Dissolvable support material is now starting to become a more commonplace feature of future desktop 3D printers.

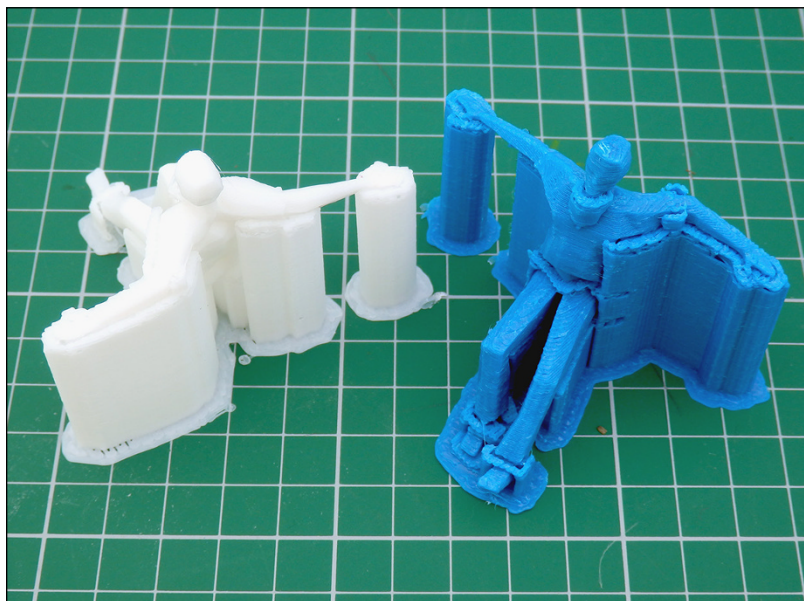


FIGURE 15-4: Take care when removing the support material; small, fragile parts can be damaged or snapped off.

3D printers like the BCN3D Sigma (see Figure 15-6) use a dual X-carriage system that allows two different materials to be printed with independent extrusion and movement systems. A primary material can be loaded and used on the left extrusion system while the right system is parked. When a support structure is required, the left head can park, and the right head takes over. This system allows much more freedom in model creation.



REMEMBER

Desktop 3D printers are not quite at the point of being able to print “anything” — for example, very fine details in jewelry where even support material can’t “support” the fine structures using the thermoplastic materials we have available — but the technology is moving in the right direction.

You can get around (or minimize) the use of support material by rotating the model in a software program like Netfabb before printing. (See Chapter 11 for a Netfabb overview.) If you rotate a model of a seated person so that the back and arms are on the base of the print surface, for example, you may not have to use support material at all. (See Figure 15-7.)

FIGURE 15-5:
This support structure is mostly hollow and easily removable with needle-nose pliers. Further cleanup may require a sharp blade or small file.

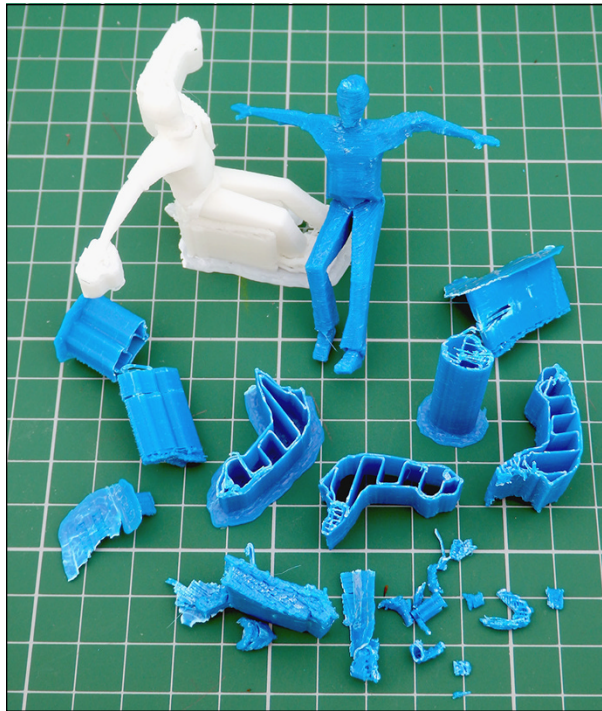


FIGURE 15-6:
The dual independent carriages of the BCN3D Sigma allow you to use two different materials without one oozing on the other or getting in the way of printing.

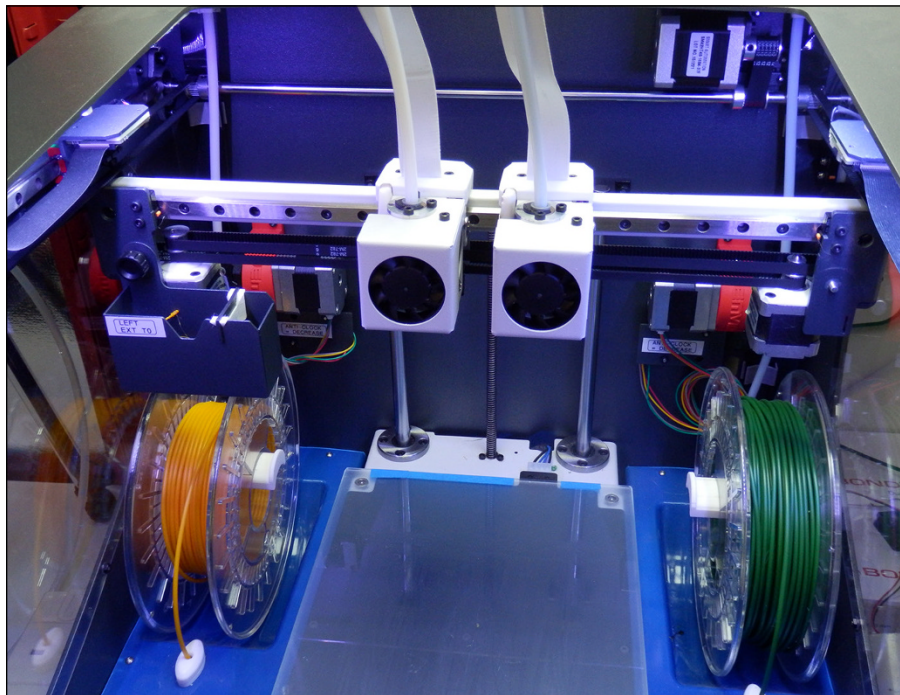
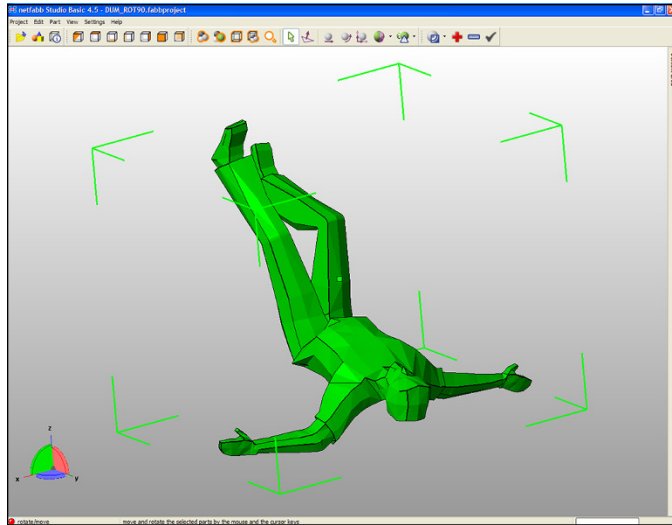


FIGURE 15-7:
Rotating a model
in Netfabb to
make printing
easier.



No wonder 3D-printing sites often provide models designed for home 3D printing. A model of a person would most likely be posed standing straight up, with hands by the sides or in contact with the upper legs. In either case, no extra support material is needed, so the model can be printed easily on a home 3D printer. Most home users would struggle to print models in more complicated poses, due to the way that 3D printers build up a model layer by layer. For this reason, if you require a model of a seated person, you may have to use support material. (Refer to Figures 15-4 and 15-5.)



TIP

You may be better off dividing complicated objects into subassemblies. All parts are printed flat on the build plate and later assembled into complex, functioning objects. A gearbox is a real challenge — even for a professional-grade 3D printer — to build as one complete, functioning object with no manual assembly required. Stay tuned, though; this goal is getting closer all the time.

Using design software

Many software packages for designing 3D models are available and — thankfully — many are open-source or free and include export options that support the STL model format used by RepRap 3D printers.

One popular option for RepRap developers is OpenSCAD (www.openscad.org), shown in Figure 15-8. This free and open-source 3D modeling program is built and maintained by individuals devoted to keeping it freely available. OpenSCAD has an ever-expanding and comprehensive array of examples, libraries, and resources. It allows *parametric modeling*, which allows you to change almost any of

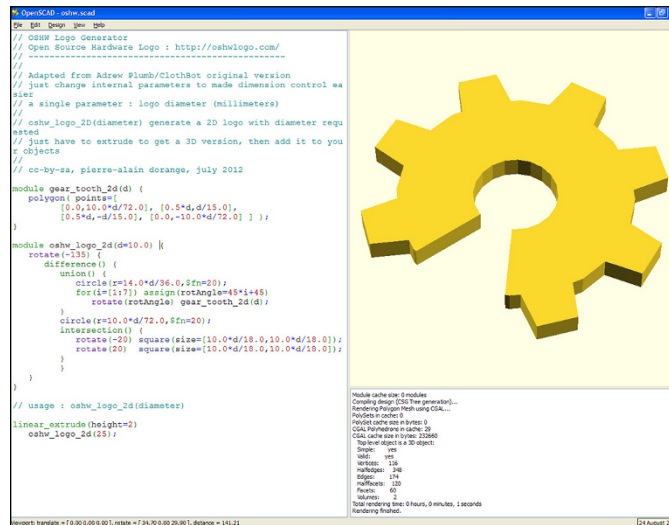
a design's dimensions, shapes, or features by altering the appropriate *parameters* (numbers or formula). With parametric modeling, you can specify a generic model of a shoe insole then enter specific details about your foot, size, shape, and the desired level of comfort (flexibility in the material). The parametric software modifies and produces a new custom-fitted 3D model based on the settings you entered.



WARNING

One clear downside of OpenSCAD is that it's quite complex. Unless you're familiar with programming and have a good mathematical grasp of geometric 3D space, you may struggle to work with this software.

FIGURE 15-8: Because of its parametric nature, OpenSCAD can accommodate many options with a small change of code.



Another popular package is SketchUp Make. This visual modeling tool is a good program to use to experiment with your own designs or alter existing 3D models. Find it at www.sketchup.com/download/all.



TIP

You can use almost any type of 3D-modeling program. Many programs now exist as cloud-based applications that produce customized 3D models (or allow you to make those models easily).

Many more consumer-level software products are specifically designed for 3D printing. All provide easy-to-use applications for modeling objects designed for home, hobby, or business 3D printing. Examples include:

- » TinkerCAD (www.tinkercad.com)
- » Meshmixer (www.meshmixer.com)

- » Autodesk Fusion 360 (<http://www.autodesk.com/products/fusion-360/overview>)
- » SolidWorks (www.solidworks.co.uk/)
- » Rhinoceros (www.rhino3d.co.uk/)
- » Autodesk Remake (<http://remake.autodesk.com/about>)
- » SharkCAD (www.punchcad.com)
- » Blender3D (www.blender.org/)
- » FreeCAD (www.freecad.org/)

The output format you require for a 3D printer is Stereo Lithography (STL). This file format is usually available as a standard export option, although some packages require a plug-in. If you've already obtained an STL model file from an object repository or as an export file from your 3D modeling program, check the model to make sure that it works with your software, as discussed in the next section, "Verifying models with Netfabb."

Verifying models with Netfabb

If you have an STL model file, you have to verify the model before you can print it. Software programs and slicing tools for 3D printing see all 3D models, including solids, as a series of triangles that join to create a hollow mesh surface. The triangles in your model must not intersect other triangles; if they do, they create an invalid mesh that causes problems if you try to 3D-print the model.

It's a good idea to verify that your model export or download is a *valid mesh*. A valid mesh for 3D printing is one that has a complete surface with no gaps — a state often referred to as *manifold* or *watertight*. All STL 3D models for 3D printing are exported as a hollow shell. (Think "inflated balloon" if you want to visualize it.) The model, like a balloon, has both an outer and an inner surface (skin) defined by many connected triangles to form the surface, with nothing inside the skin. If you had a hole in the balloon or 3D model the structure would not be viable.



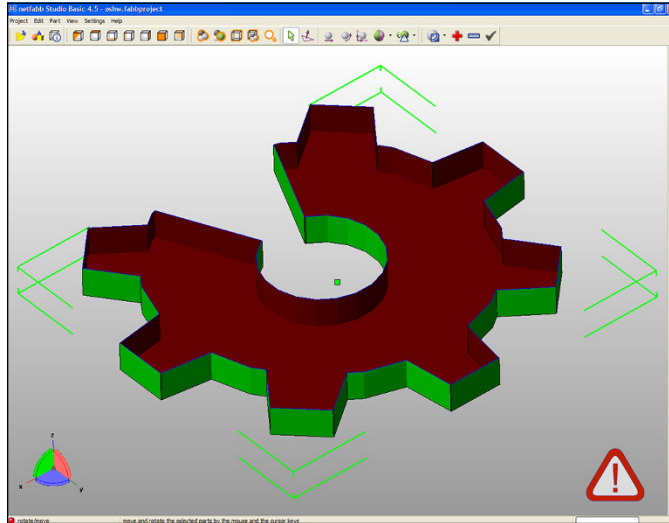
REMEMBER

If a 3D model has missing triangles that produce holes in the mesh surface, it is no longer a valid 3D model. Triangles of a model can also be accidentally flipped, causing sections of the inner and outer surfaces to become reversed. One of the most common modeling and export errors occurs with triangles that are not joined as a surface, but intersect each other, causing great confusion when trying to carry out a 3D print job.

Finally, you need to have the 3D model in the correct orientation for 3D printing and you need to check that the size is what you expect and require. Netfabb Basic

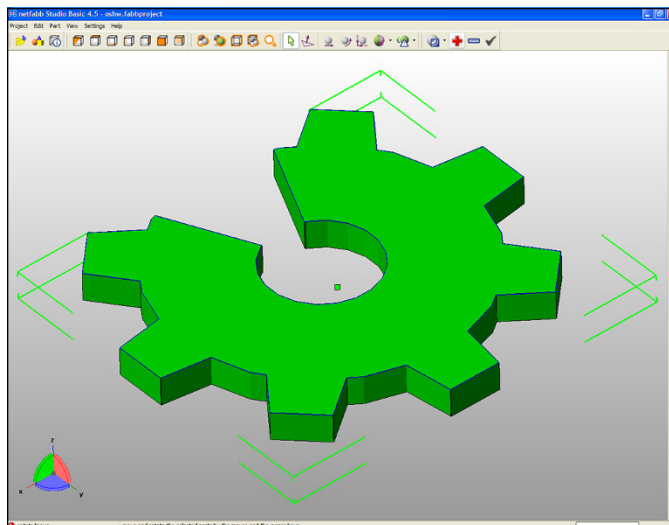
works well for this sort of checking because it highlights problems with exclamation marks and shows the orientation onscreen, allowing you to repair, scale, and reorient the model as needed for export and 3D printing. (See Figure 15-9.)

FIGURE 15-9:
Netfabb highlights problems in your model with exclamation marks.



When mesh errors are present, you can use Netfabb to make repairs. After rotating and scaling the model as needed, click the + (plus) button to attempt a repair. Then select Standard Repair and click Apply Repair to obtain a new model that you can then export for 3D printing. (See Figure 15-10.)

FIGURE 15-10:
Netfabb detected that this model isn't solid. After repair, the solid model can be 3D-printed.



Working with PrusaSlicer

PrusaSlicer, descended from the original open-source Slic3r software created by Alessandro Ranellucci, is a print-slicing program that processes 3D models for printing. You can download the PrusaSlicer software (or alternatives such as Cur) for PC, Mac, and Linux at <https://github.com/prusa3d/PrusaSlicer/releases>. Before you work with the material in this chapter, I recommend that you download and install PrusaSlicer on your computer so you can experiment with the various settings for 3D-printing models.

Configuring PrusaSlicer

After successfully installing PrusaSlicer, you still have to configure it. The software needs to know several key settings linked to your particular 3D printer. You enter these settings using the configuration wizard that appears when you first start the program. In the following steps, I'll be selecting the Prusa MINI 3D printer during the wizard setup but you, of course, will have to enter the details for your specific 3D printer type. Doing that sets up the correct profile for you to use. Alternatively, check whether your 3D printer manufacturer already has a configuration package setup for PrusaSlicer or Cura.

Time to configure!

1. Launch the PrusaSlicer program.

On first launch, the configuration wizard springs into action, as shown in Figure 15-11.

2. Click Next in the wizard's Welcome screen.

3. In the next screen that appears (see Figure 15-12), select the Prusa printer you want from the displayed list (or multiple printers if you have more than one type) and then click Next.



REMEMBER

If you have a printer from the already configured list, you may be able to select a make and model from another 3D-printer supplier. PrusaSlicer supports many standard models as well as fully customized configurations.

To configure PrusaSlicer for a different 3D printer follow these steps:

a. After selecting the Custom Printer tab in the Configuration wizard, select the style of Gcode to use with the firmware you'll be running on your desktop / RepRap 3D printer in the new screen that appears (see Figure 15-13) and then click Next.

Usually, this Gcode is RepRap (Marlin/Sprinter) as that's the most common type of firmware and tends to also be most compatible with other variants, so it's a good choice.

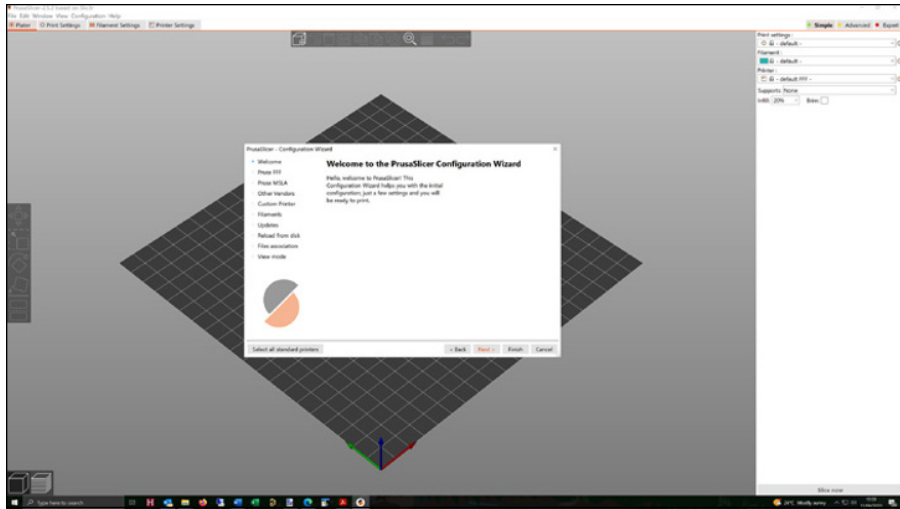


FIGURE 15-11:
PrusaSlicer setup wizard.

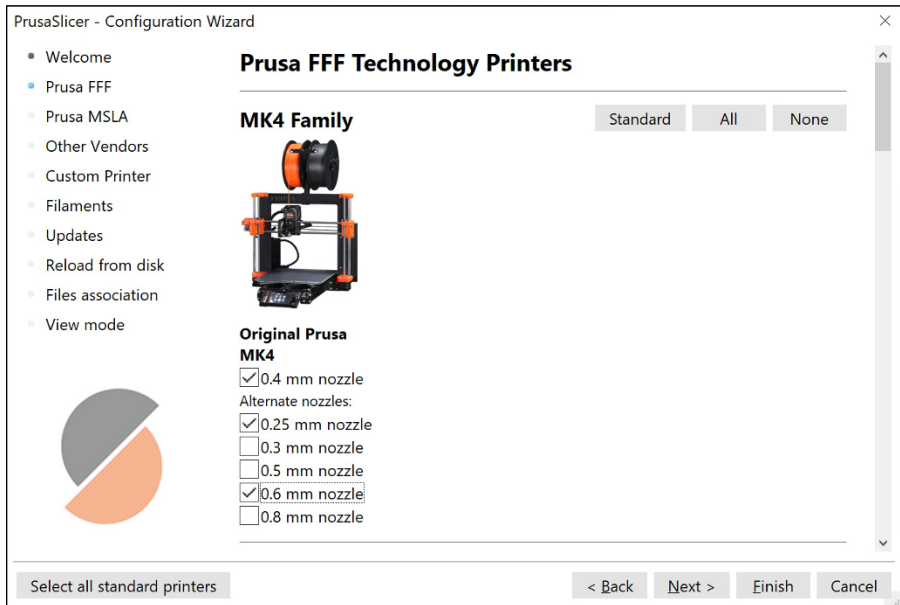


FIGURE 15-12:
PrusaSlicer setup and selection of 3D printer types.

b. In the new screen that appears, enter the size of your printer's build bed and click Next.

For a RepRap that uses a Prusa-style heated bed of printed circuit board (PCB) material, enter 200mm × 200mm. A Delta printer has a rounder build area, which you have to consider when you're printing objects, but you can enter the size as X and Y coordinates.

c. In the new screen that appears, enter the size of the output nozzle on your 3D printer's hot-end and click Next.

Common sizes are 0.5mm, 0.4mm, and 0.35mm. PrusaSlicer uses this information to calculate the gap and material extrusion flow rate required between the extruder nozzle and part surface necessary to extrude each layer so that each layer bonds securely to the one beneath it. This setting serves as a guide for PrusaSlicer; tuning the width and height of the extrusion path is a separate, independent part of the calibration process.



TIP

The extruded width of the output also depends on many tiny aspects of the hot-end design. Many materials will experience some *die swell* — when molten plastic material expands under pressure on exiting the tiny nozzle; the output filament expands from the nozzle as it exits, swelling to a diameter greater than the nozzle size. Print calibration, then, is important to prevent extruded plastic layers from extruding too closely together or too far apart. In either situation, your 3D models won't look right or won't function correctly.

d. In the new screen that appears, enter the filament diameter and click Next.

Be sure to measure the diameter of your filament, get the best average, and enter that result as the filament diameter for PrusaSlicer — preferably after you ponder the cautionary sidebar “Check your filament carefully.”



WARNING

Newcomers to 3D printing who discover a lack of material or over-extrusion on their printed objects often change the filament diameter setting to adjust the volume of material. This method can work, but as a rule, I don't recommend it. Inaccurate extrusion often masks a bigger problem with extruder calibration or machine setup. These problems manifest themselves as poor print quality, over-extrusion of material, and an incorrect fit for holes and apertures. Any fudge-factor applied to settings leads to inaccurate calculation of print time and material being used. Use an accurate measurement for filament diameter, and never adjust this number to tweak the volume of plastic being extruded.

4. Assuming you have selected the correct printer and clicked Next, select the filament profile you're planning on using in the next screen that appears (see Figure 15-14) and then click Next.

You can select multiple filament types from the displayed list of suppliers and material types. Don't worry if you don't select many types here; you can add more of these standard types or even enter a custom profile at any time in the future after initial setup.



REMEMBER

Keep in mind that you can change all these settings later if you need to. For now, enter as many of the specified details you can. You can save different configurations later. This arrangement is useful when you're running several machines, testing upgrades, or trying different material types.

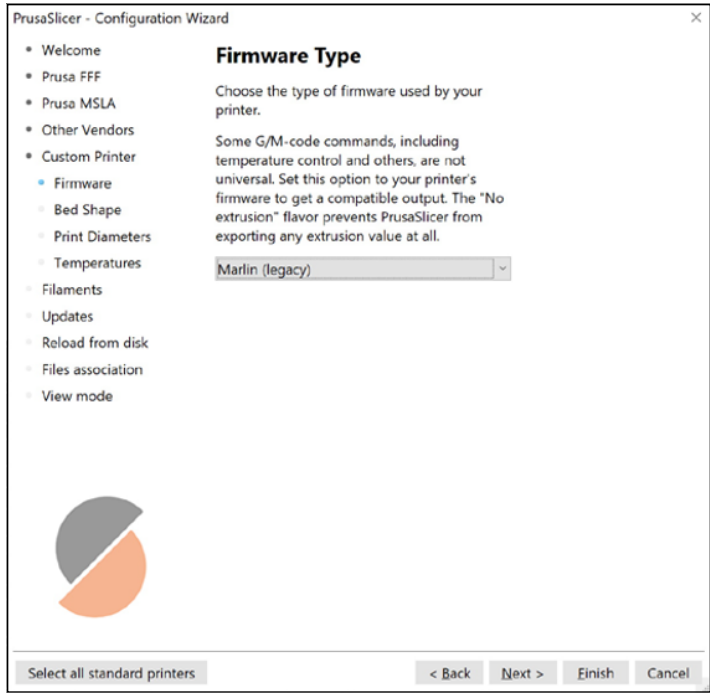


FIGURE 15-13: Choosing the Gcode for your firmware.

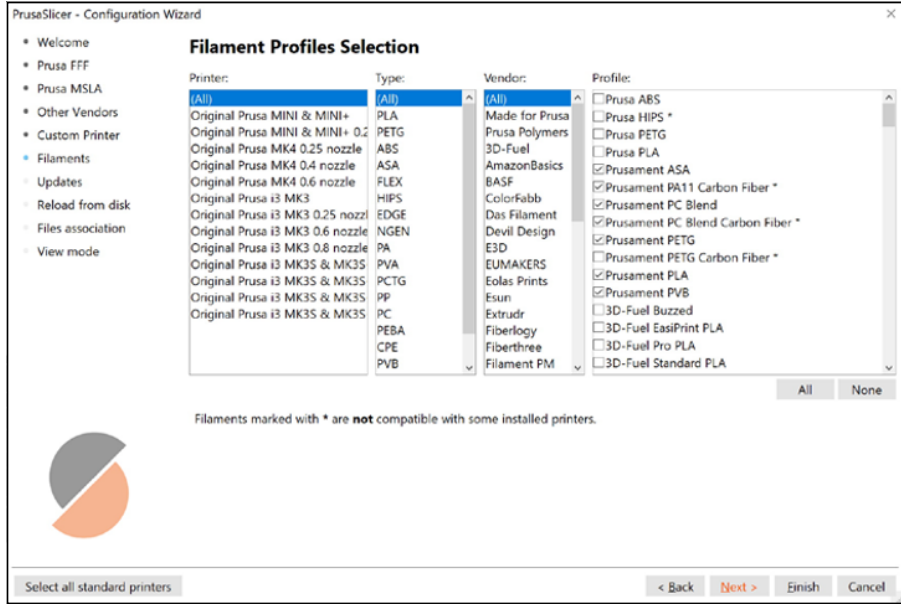


FIGURE 15-14: Select the types of material filaments you have or may want to use in the future.

5. Continue with the PrusaSlicer configuration wizard, setting up your extrusion temperatures and selecting heated bed temperature settings.

The extrusion temperature of a thermoplastic in 3D printing has to be high enough to allow your extruder to push material consistently into the hot-end without stalling, but not so high that the plastic gets runny and overheated, which causes it to break down and smoke. You will need to set up the extrusion temperatures for common types of plastic you are likely to extrude in your 3D printer. For PLA, the temperature is around 200° C; for acrylonitrile butadiene styrene (ABS), the temperature is around 240° C.



TIP

Usually, you need to increase printing temperatures when you print significantly faster than normal. More energy needs to be transferred more quickly into the faster melting plastic flow. On the other hand, when printing a tiny, detailed object slowly, you often need to reduce the print temperature to limit oozing of the plastic. (Too much thermal energy produces oozing.) For more on setting extrusion temperatures, see the “Tuning your hot-end temperature control” section, later in this chapter.

6. If your RepRap 3D printer has a heated bed, enter a temperature value for the material that you intend to print.

Again, don't worry if you plan to print different materials; you can set up multiple configurations in PrusaSlicer later. As a guide, use 60° C for PLA and 110° C for ABS. If you want to print without using a heated bed, leave this value set to 0.



TIP

Almost every desktop 3D printer needs to be tuned for specific printing temperatures. It's fine to use other people's suggestions as a guide, but exact locations of the temperature sensor and small variations in the electronics and firmware setup may give you a very different reading on your specific machine.

CHECK YOUR FILAMENT CAREFULLY

A consistent filament diameter that extrudes with a round — not oval — cross section is critical to 3D-printing success. PrusaSlicer needs to know the size of your input filament so it can calculate the volume of plastic that it commands the 3D printer to push out of the hot-end while the head is moving around the object. If this setting is incorrect, or if your material changes in diameter during a print, you've got trouble:

- You run the risk of over-extruding. Then your print head may jam or skew and ruin your print.
- The print head may under-extrude your material, resulting in a weak print, delamination, or just an ugly object.

(continued)

(continued)

Good filament should have a round cross section that doesn't deviate more than 0.1mm. Oval filament is a potential 3D-printing disaster; it changes in volume in your hot-end, depending on how the extruder pinch wheel grips it. The result is a mess. If you find that your filament has an oval cross section, complain to the supplier and reject the filament if it causes problems.

The best way to get an average size for your filament is to measure ten points along a few meters of material by using a micrometer. Check whether the filament is round by rotating the micrometer at the same point. Add these measurements together and divide by ten. You should have an average value that shows a tolerance of around 0.1mm deviation if you're using suitable-quality filament.

You can trust the diameter information provided by your supplier, but it's well worth taking the time to measure your material, especially if you use different suppliers or different materials. **Note:** The actual size of 3mm filament is often 2.85mm. This size is normal; it allows the filament to be driven down tubes used in 3mm-diameter hot-ends and extruders.

Processing models with PrusaSlicer

After PrusaSlicer is installed and configured, you can use it to process your valid model. PrusaSlicer processes your model to create an output Gcode file, ready for printing.



TIP

The example in this section runs PrusaSlicer in Simple mode. When you become more familiar with your 3D printer and its capabilities, you can use the configuration wizard to switch to Advanced or Expert mode, which offers many more options. (See Figure 15-15.)



TIP

PrusaSlicer is continually being modified and upgraded, so use the following steps as a general guide for preparing an object for 3D printing and outputting the Gcode file. Expect changes in the user interface, options, and the degree to which the program detects the best settings for objects.

Follow these general steps to process your valid model:

1. Position the model for printing by loading it into PrusaSlicer.

When you have a valid model correctly oriented and scaled, load it into PrusaSlicer by dropping the file into the virtual build plate window, which provides a 1-1 scale view looking at your 3D models on the virtual build surface of the 3D printer. (See Figure 15-16.) You can load, move, and rotate other objects on the virtual build plate if necessary.

FIGURE 15-15:
PrusaSlicer selection of Simple mode reduces the options you need to worry about.

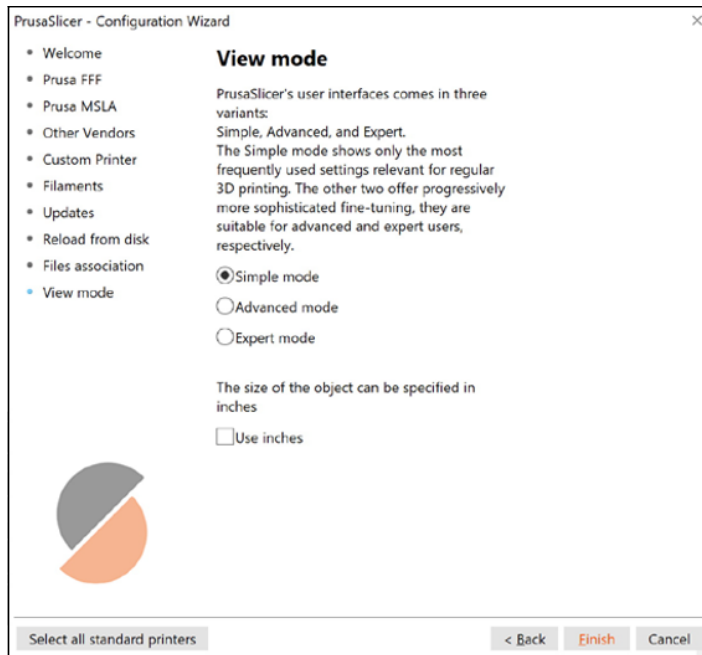
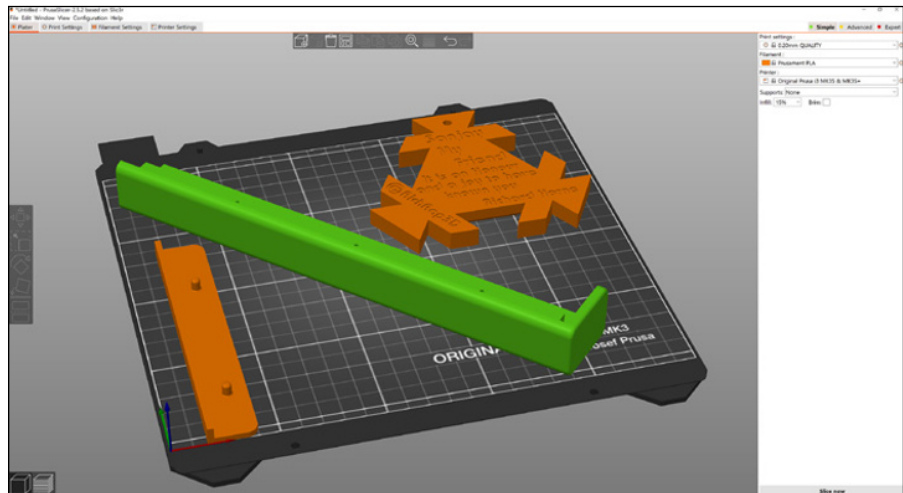


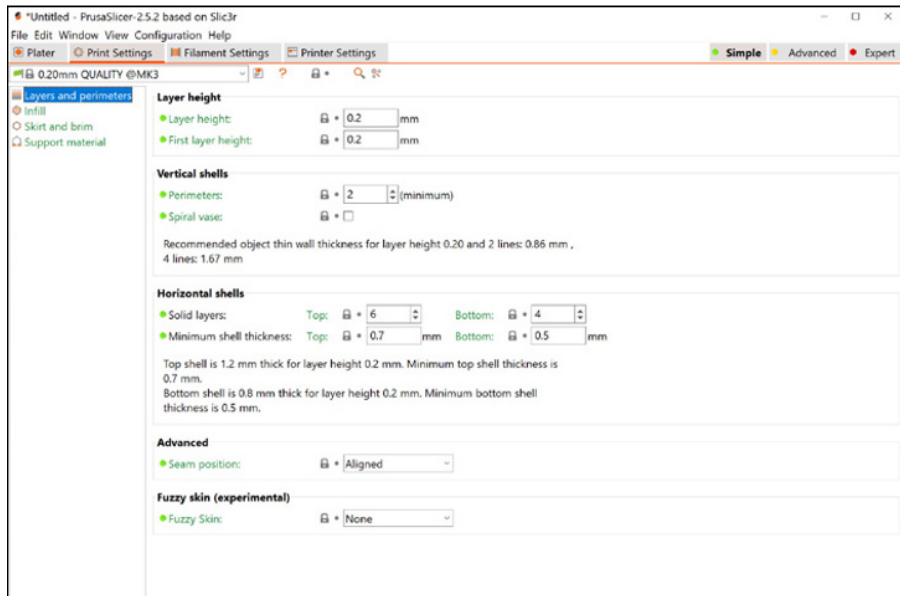
FIGURE 15-16:
The Plater window provides a virtual build plate on which you can place your 3D objects before processing.



2. On the Print Settings tab, select suitable print settings for your model.

The Print Settings tab (see Figure 15-17) provides options that tell PrusaSlicer how you want the model to be printed and at what speed and quality.

FIGURE 15-17: The Print Settings tab in PrusaSlicer allows you to describe how solid your printed part will be and the speed at which to print it.



Choosing Layers and Perimeters from the navigation menu on the left gets you the following options:

- *Layer Height*: This setting determines how finely your model is vertically sliced. The finer the layers, the better your finished print looks, but the longer it takes to print. A typical layer height is 0.25mm for a 0.4mm or 0.5mm nozzle.
- *Perimeters (Minimum)*: This setting is the number of times the extruder draws the outer surface of a layer before doing the infill. Normally, you use at least two perimeters to ensure a solid, good-looking object.
- *Solid Layers*: The Top and Bottom settings ensure that the top and bottom of an object are solid. For most models, it's good to start with three top and bottom layers.



TIP

If you select zero top layers and no infill, your model is printed as an outer shell with as many perimeters as you selected — ideal for printing pots, vases, and other types of hollow objects. I discuss other options for printing pots in the “Printing vases, pots, and cups” section, later in the chapter.

Choosing Infill gets you the following:

- *Fill Density*: This setting is as a percentage, so a setting of 0.25 creates a 25 percent level of plastic infill for an object. A level of 0.3 (30 percent) is a good setting for most functional parts.



TIP

The objects you print almost never require an infill of 100 percent. You don't need to use more plastic to achieve only a slight gain in strength. Normally, display models are printed with less than 15 percent infill. Functional parts such as those needed to build a 3D printer usually require infill of 25 percent to 50 percent.

- *Fill Pattern:* This setting allows you to specify how the interior of an object is filled. The most common fill-pattern settings are Rectilinear and Honeycomb; Concentric is often used for round parts or for vases, pots, and so on. For mechanical parts, Honeycomb is the strongest setting, but it's slightly slower to print than Rectilinear.



REMEMBER

Some settings are only available in different view modes in PrusaSlicer. If you can't see a setting in the Simple or Advanced mode (tabs in the top right hand corner) then switch to Expert mode. I do discuss some of the options that are more advanced or expert in the steps below, but you probably don't need to tinker with these until you become comfortable with Simple mode.

Choosing the Support Material option from the navigation menu on the left gets you to the following settings:

- *Generate Support Material:* Select this setting to generate automatic support material if your object has significant overhanging features. The Raft option, which is rarely used, builds a plastic raft on the build platform before the object is printed. This setting can minimize warping in some types of plastic and can help correct for unlevel build platforms. Both rafts and support material need to be removed from the printed model; the raft or support is then discarded. You can select various patterns and spacing of rafts and support material to aid with both structural support as well as removal after printing. You need to experiment to find your ideal support or raft settings, as this tends to be specific to both the 3D printer and material being used. The ideal combination allows for just enough structure to hold the model but make it easy to peel away the support material after it's cooled.
- *Perimeters, Infill, and Travel:* The settings in the Speed section govern how fast the machine builds the object. Your electronics firmware sets the maximum speed and acceleration. Go ahead and experiment with this setting but start with a slow setting to get a good sense of how fast your particular RepRap can go and what issues you face when speeding up or slowing down printing. Most modern RepRap 3D printers can print perimeters at 50mm per second and infill at 70mm per second or faster.

Travel speed is the speed at which the machine moves from one point to another between extrusions of material. You want the print head to move as fast as possible to each new position between stops and starts of a

layer. The goal is to minimize print time and improve overall quality. Start at 150mm per second and move up in small steps. Top travel speed for a RepRap printer with an extruder mounted on the moving carriage is around 280mm per second. A lightweight Bowden extruder or a Delta printer should be able to exceed 400mm per second. (Only a few years ago, home 3D printers were ten times slower.)

- *Brim Width:* I discuss this setting later in this chapter in the “Printing large single-piece objects” section.
- *Sequential Printing:* Set this if you want to print each object on your build plate one at a time. Normally, you’d print an entire plate of parts layer after layer, which is usually the fastest way to print. However, printing the entire plate at once means that if you have a fault in the print or if one of the objects becomes detached, the entire build will be ruined. With sequential printing, you print each part one at a time; this can limit the failures, but it takes longer. Also, because your extruder must be able to print around an already-printed object, you’ll have to enter the clearance distance of your hot-end so it doesn’t crash into an already-finished part. This arrangement also limits how many parts you can place on the build platform.

3. On the Filament Settings tab (see Figure 15-18), select your print material size and temperature.

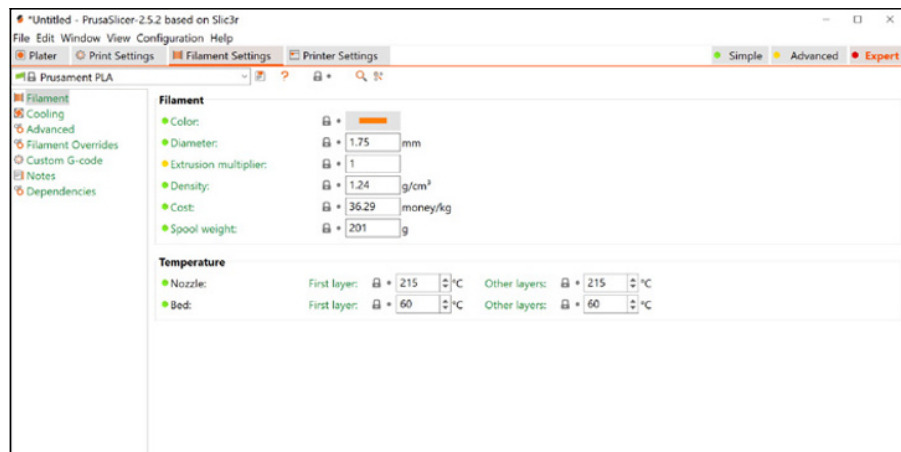
Tell PrusaSlicer the diameter of your filament and the temperature at which to extrude it based on the material being used. You can also tell PrusaSlicer to use a heated bed, if your printer has one.

Make sure that the measured diameter of your filament is correct. If you’re printing with PLA, you should set an extruder temperature of around 200° C and a heated-bed temperature of 60° C.



REMEMBER

FIGURE 15-18: The Filament Settings tab tells PrusaSlicer what material you’re using and what temperature should be used for the material (filament) being used.





TIP

You have the option to increase the temperature a little for the first layer. This setting is useful if the plastic isn't sticking to the build platform, but don't go too high; excess heat may keep the material from sticking.

4. On the Printer Settings tab (see Figure 15-19), set your 3D printer size and extruder setup, nozzle size, and general machine configurations.

This tab should already show the mechanical size of your 3D printer, since you set it when you first ran the configuration wizard during the first startup. In the machine limits, you can check that the Bed Size and Print Center settings are what you expect for your machine. The other options on this tab include the following (depending on whether you are in Simple, Advanced, or Expert display mode):

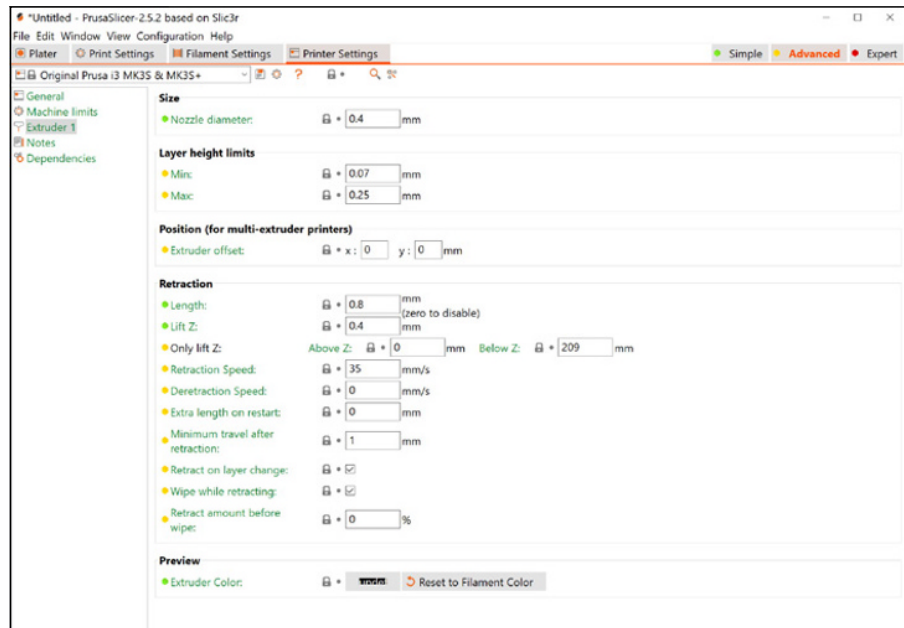


FIGURE 15-19:
The Printer Settings tab will show your extruder settings and machine configuration based on the model selected.

- *Z Offset:* This setting is useful if you're running different extruders with hot-ends of different lengths or if the nozzle is fractionally too far from or too close to your build surface. Enter a positive value to raise the hot-end from the build surface before printing starts. Depending on how your 3D printer is configured, you may not be able to enter a negative number to lower the hot-end before printing. In that case, you usually can adjust the hot-end mechanically. I discuss this technique in more detail in the "Calibrating Your 3D Printer" section, later in this chapter.

- *GCode Flavor*: This setting specifies the type of open-source firmware you have in your electronics. For a RepRap, you usually choose the option titled RepRap (Marlin/Sprinter/Repetier). Check with your supplier if your 3D printer isn't a RepRap.
- *Nozzle Diameter*: Check this setting to ensure that your nozzle diameter is correct.
- *Length*: The length of extruder retraction is a very important aspect of the printing process. Unfortunately different thermoplastic materials that are being used for printing require a different length of extruder retraction to stop plastic ooze or missing print sections. This retraction length is a move to suck back the melted filament into the hot-end after a section of printing. Usually it happens before the hot-end travels to a new point on the build plate where another section of material will be deposited. You only need to specify a retraction length; the firmware knows to move the filament back the same distance when it reaches the next printing point before it starts extruding. You need to use this setting to prevent blobs and fine strings of melted plastic from making a mess of your print. Make sure you have retraction enabled and set at least 0.5mm. If you still have problems with blobs or fine strings across areas of your model, then increase this length 0.2mm at a time. In most 3D printers, you should not need more than 2mm but do check with the manufacturer as some Bowden configurations may require up to 4.5mm, which is the maximum length you should set.



REMEMBER

Every extruder setup is different. Experiment to find the best degree of extruder retraction and keep in mind that you must adjust this figure to suit the material you're using. For a geared or direct-driven extruder, start with 0.5mm of retraction; a setting of around 1.5mm may be required to stop strings and blobs. Don't set the retraction value too high; air may be sucked into the nozzle if you do, causing many other problems. A Bowden requires significantly longer retraction due to the elastic nature of the filament being pushed inside the PTFE (Teflon) tube; approximate retraction values can range from 1.5mm to 5mm.

- *Lift Z*: This setting allows the extruder to lift a little above the object being printed right after the extruder retraction and just before the machine-travel move. Lift Z gives the fast-moving print head a little more clearance when it's moving across a printed layer to get to a new point to print. Enter a positive number — usually, one extra layer height. (This is the same as your selected layer height, which you specified in the Print Settings tab — for example, 0.25mm). As with the extruder retraction, the firmware knows to go back down by the same amount when the travel move is complete and before the next extrusion starts. This setting can help if your

objects are being knocked off the print bed during printing or if layers are skewed out of alignment because the motors are hitting corners or already-printed components of the object.



TIP

If Lift Z doesn't keep objects from being knocked off or printed layers from shifting, the travel moves may be too fast. In such a case, try slowing the travel on the Print Settings tab. If that change doesn't resolve the issue, the extruder is most likely over-extruding plastic material that's getting caught on the hot-end during printing. For more about ensuring correct extruder calibration, see the "Calibrating extruder distance" section, later in this chapter.

- *Start GCode and End GCode:* These commands start and finish every print. These Gcode instructions are added to the output of every part printed; they tell the firmware how to set up the specific RepRap 3D printer for printing and how to shut it down.

The standard starting Gcode in PrusaSlicer tells your printer to go to the home position and lift the nozzle a little. Your print starts after the extruder head and heated bed reach the temperature you specified on the Filament Settings tab of PrusaSlicer. (Refer to Step 3.) The end Gcode shuts off the extruder and bed heaters and then homes the printer on the *X* axis; you don't want to crash the carriage into the printed object. Finally, all the stepper motors are disabled, so the machine is in a running-but-shut-down state.



TECHNICAL
STUFF

Eventually, you may want to add more custom Gcode commands. Many RepRap electronics, for example, now have an onboard sounder that can play beeps and alerts. You can control it by specifying (in the starting Gcode) three short beeps at the start of a print; you may want to specify a long and loud beep to signal the end of the print in the ending Gcode. You can control many other operations with Gcode, such as turning on fans at the end of the print to cool the printed object and build bed. Another option, available in PrusaSlicer's Expert mode, triggers a digital camera to take an image after every layer is printed, which can provide a stop-motion high-speed video of your object growing as it prints.

5. On the Plater tab, click the Export Gcode button.

Depending on the complexity of the objects being printed, the performance of your computer, and the fineness of the layers you selected, exporting the Gcode file can take a few seconds, a few minutes, or (in extreme cases) hours. Things take time; complex things take more time. If no warnings were displayed, your Gcode should be ready for your printer. Before you print, however, make sure that the 3D printer is calibrated, as I discuss in the next section, "Calibrating Your 3D Printer."

Calibrating Your 3D Printer

After you've set up your firmware and done most of the calibration for your RepRap printer's mechanical movement, you still need to complete a few tasks before 3D printing can take place:

- » Make final calibrations of the extruder and hot-end.
- » Enter these calibration details into the firmware.
- » Compile and download the firmware again if required or change the settings on your 3D printer.

The sections that follow are intended to provide guidance for a number of desktop 3D printers. If you happen to have a dedicated machine such as the Prusa MINI or the I3 MK2/3/4, then much of this setup and calibration has already been done at the factory for the specific design of the printer. However, if you make changes, such as changing from a brass nozzle to a hardened steel one or swapping out the extrusion system for one with a different design, you will need to understand and know how to update settings and configurations of the machine to accommodate the changes. If you end up not taking the time to do this, your machine will not operate or print correctly.



REMEMBER

Don't be tempted to skip these calibration tasks. Correct calibration of the extruder and hot-end makes all the difference between an awful-looking print and a stunningly good one.

The procedures in this section use the Pronterface application for controlling your printer. (See Figure 15-20.) You can run any of the other host programs I discuss in this chapter, but I'm using Pronterface for this initial setup because it's easy to use.

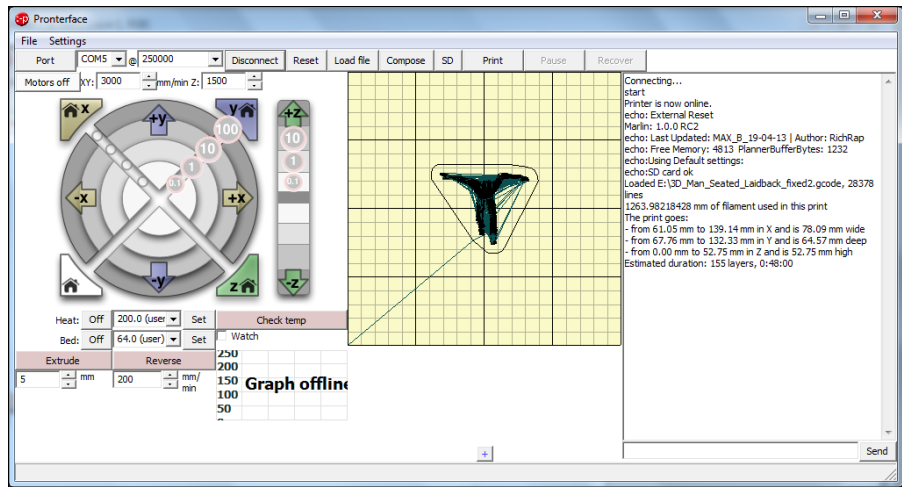


TECHNICAL
STUFF

Pronterface was designed and programmed by Kliment Yanev as an open-source control interface for RepRap 3D printers. You can obtain the full package (called Printron) at <https://github.com/kliment/Printrun>.

It's also quite possible to perform many of these functions directly on your 3D printer's own control panel/screen. If all you have to do is move an axis, home the printer, or extrude some filament, you can usually handle those chores right from the 3D printer control's menu.

FIGURE 15-20: Pronterface running and connected to a RepRap printer with Gcode loaded and ready to print.



REMEMBER

Unlike 2D paper printers that appear in all applications as printers, most 3D printers require a host program to prepare, control, and send the specific Gcode file. That means that, when you are at this point in the printing process, you can't just turn on the machine and press Print. You need to do a little more with a 3D printer. Here are the steps you'd follow if you're using Pronterface:

1. **Launch Pronterface on your computer.**
2. **Connect the 3D printer to your computer via USB cable and turn on the printer.**
3. **Select the desired communication port from the drop-down list in the upper left of the Pronterface main window. (Refer to Figure 15-20.)**
4. **Make sure that the correct speed is selected from the neighboring drop-down list in the Pronterface main window. (Again, refer to Figure 15-20.)**

For Marlin firmware, this speed is normally 250,000.

5. **Click Connect.**

If the communication port and speed have been set correctly, you see a message in the right-side window in Pronterface that indicates the connection and communication are active. This message signals that you have control of the printer and that it's ready to accept commands.

Leveling your print bed

The first order of calibration business is making sure that your hot-end nozzle is a set distance from the print surface and that your printing surface is flat and level.

The procedure varies from one 3D printer to the next. Usually, it involves tightening or slackening three or four points on your build bed, which usually is made of PCB material and fixed or held by spring bolts that allow you to level the bed.

If you have an automatic bed leveling system, that's great, but do make sure to manually level the surface in relation to the nozzle and X, Y, Z axis as best you can. This way, the automatic bed leveling will not need to add too much compensation to a particularly angled bed or a twisted and un-level surface.



REMEMBER

Before you level the bed, make sure that the other major assemblies of your 3D printer — especially the moving X carriage and the vertical Z movement — are also level and at equal distance on each side.

The main sensor that positions the hot-end correctly away from the build bed is the Z-axis end-stop. Usually, this sensor is either a mechanical switch that can be moved up and down or it's a magnetic sensor that can sometimes be tuned to a set distance by turning a small rotary knob known as a *potentiometer*. Commonly, a small LED on the end-stop-sensor lights when the end-stop position is reached. If your axis doesn't stop, or if the LED doesn't light when the axis is sent to the home position, you may have an incorrect orientation set in your firmware (as discussed in Chapter 13). In such a case, change the `X_ENDSTOP_INVERTING = true` setting to `false` in the `configuration.h` file of the Marlin firmware. For 3D printers like the Prusa MINI or Prusa i3 MK2/3/4, you can also physically adjust the PINDA probe up and down to set a suitable distance. The offset calibration is then carried out by the machine itself.

For the Prusa MINI, the bed level and mesh leveling routines are performed during the setup. These settings, along with the offset distance, are then set into the firmware by the printer and should only need changing when the nozzle starts to wear down and the distance to the build surface increases.

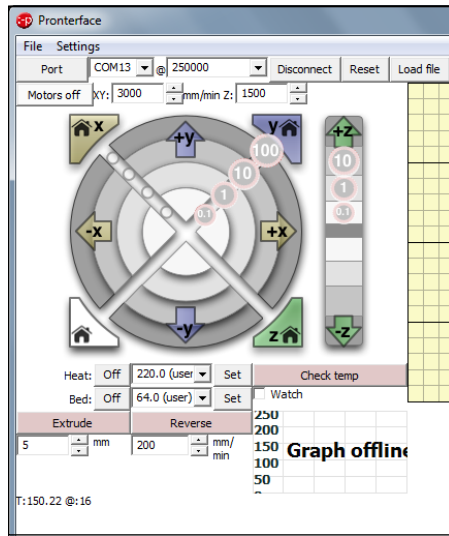


REMEMBER

If you use a heated bed, make sure that it's powered on and at full temperature for at least a few minutes (to allow everything to expand to where it will be when printing) before you set the mechanical distance of the hot-end nozzle from the bed.

Check the operation of the end-stop switches by commanding each axis in turn to move to the home position. (Figure 15-21 shows the pertinent controls in Pronter-face.) Then set the Z-axis distance so that the hot-end nozzle is spaced appropriately far from the bed. The best way to do so is to move the print head to the center of the bed. For a standard RepRap printer, you set this space by moving X by 100mm and Y by 100mm.

FIGURE 15-21:
 You can use Pronterface controls to position the print head for leveling the bed, setting the correct distance for the hot-end nozzle, and pre-heating before printing.



Often, the 3D printer assists you with this process via its own LCD screen or user interface. You may first have to rotate a screw wheel to adjust the bed position. The sensor then checks the leveling and informs you if any further adjustments are required. When everything is level, you can continue with printing, knowing that the first layer should go down smoothly and evenly.



REMEMBER

The Z-axis distance you need to achieve depends somewhat on the nozzle size and on how well you leveled the build bed. Partly for this reason, a sheet of glass (which tends to be reasonably flat) is a good choice for the build surface. As a starting point, make sure that you can slide a single sheet of office paper under the nozzle when it's at the Z home position. Check this gap for uniformity in all four corners and in the center. Use the Z-movement buttons in Pronterface to lift and lower the nozzle. Then you can move the position of your Z end-stop on the Z axis to activate at the correct distance from the print bed. (Use a sheet of office paper as a spacer.) When you home the Z axis in Pronterface by clicking the Z Home button (refer to Figure 15-21), the nozzle should raise then lower until the Z end-stop is triggered. If the spacing is still incorrect, move the Z end-stop slightly and click the Z Home button again.

Tuning your hot-end temperature control

The next stage of setup is calibrating the temperature-control requirements of your hot-end. For this procedure, you enter the command `m303` in the bottom-right corner of the Pronterface screen and then click Send. (See Figure 15-22.) This command has the printer perform several heating and cooling cycles; at the end of these cycles, it gives you the settings you need to enter in the firmware (as discussed in Chapter 13) for `DEFAULT_Kp`, `DEFAULT_Ki`, and `DEFAULT_Kd` in the `configuration.h` file.

FIGURE 15-22:
The Gcode command `m303` runs an autotune routine that calculates the ideal control loop settings for your firmware.

```
Connecting...
start
Printer is now online.
echo: External Reset
Marlin 1.0.0
echo: Last Updated: Jul 3 2013 21:15:34 | Author:
(RichRap, 3DeltaRap)
Compiled: Jul 3 2013
echo: Free Memory: 4543 PlannerBufferBytes: 1232
echo:SD card ok
>>m303
SENDING:M303
PID Autotune start
bias: 112 d: 77 min: 145.90 max: 152.64
bias: 118 d: 71 min: 146.00 max: 152.95
bias: 115 d: 74 min: 147.31 max: 152.83
Ku: 34.18 Tu: 35.91
Classic PID
Kp: 20.51
Ki: 1.14
Kd: 92.06
bias: 111 d: 78 min: 147.80 max: 152.61
Ku: 41.31 Tu: 33.16
Classic PID
Kp: 24.78
Ki: 1.49
Kd: 102.73
bias: 109 d: 80 min: 147.66 max: 152.81
Ku: 39.56 Tu: 33.16
Classic PID
Kp: 23.73
Ki: 1.43
Kd: 98.38
PID Autotune finished ! Place the Kp, Ki and Kd constants in
the configuration.h
m303
```

Write down the values displayed for `DEFAULT_Kp`, `DEFAULT_Ki`, and `DEFAULT_Kd`. You'll need to enter these values in the firmware when you complete the final stage of calibration.



REMEMBER

For the Prusa i3 MK3 3D printer, these functions can be performed from the menu system of the printer. These new settings are then automatically stored so you don't need to update and flash the firmware yourself.

For the Prusa i3 MK3 3D printer, these functions can be performed from the menu system of the printer. These new settings are then automatically stored so you don't need to manually update the firmware yourself.

Calibrating extruder distance

Before you can calculate extruder distance, you need to ensure that the correct amount of plastic is extruded for a given extruder distance, perform a simple test extrusion, measure the results, and then calculate the change. Don't worry — the process isn't difficult. I'll take you through it step by step.



REMEMBER

Extruder calibration is really important. It ensures that the firmware knows exactly how much material is being deposited. That way, the PrusaSlicer program can rely on your machine for accurate calculations when producing the Gcode to print objects.

I discuss the key firmware settings in Chapter 13. Pay particular attention to the fourth number in the `DEFAULT_AXIS_STEPS_PER_UNIT` list, which specifies how many steps the extruder motor uses to feed 1mm of filament into the hot-end.

You can extrude and reverse the extruder only when it's up to temperature. This manual control is essential for loading and removing filament and for purging any old material. In Pronterface, you can command the extruder to extrude or reverse the stepper motor by a set distance (specified in millimeters, as shown in Figure 15-23).

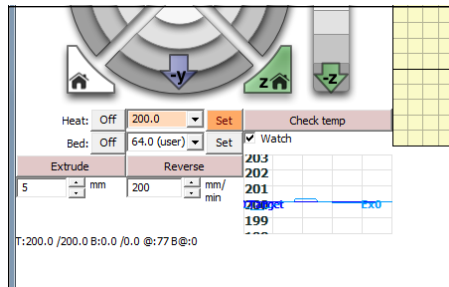


FIGURE 15-23: Controlling the extruder in Pronterface.

Calibrating your extruder ensures that the extruder axis moves exactly the number of steps per unit (each unit being 1mm) and exactly the distance you specify in Pronterface. This way, when the Gcode produced by PrusaSlicer commands a 2mm extrusion, you can be sure that the correct amount of material will be deposited. Calculate the correct value by following these steps:

- 1. Pre-heat your hot-end nozzle by selecting an appropriate temperature for the type of filament material you are using (200° C for PLA and 240° C for ABS).**

You don't need to heat your heated bed for this calibration.

- 2. When the hot-end is at temperature, insert the filament and then click the Extrude button in Pronterface. (Refer to Figure 15-23.)**

You should then see the highlighted extrude length (5mm) start to move the extruder drive motor so that a 5mm length of filament is pushed into the hot-end every time you click.



TIP

At this point, if you notice the extruder stalling, spinning, or attempting to drive the plastic filament a lot more than 5mm, you may need to lower the number in the firmware so that you can calibrate more accurately.

Depending on the type of extruder, the type of gearing it has, the electronics that were selected for it, and the way the microstep value was set, the steps-per-unit value should be somewhere between 50 and 1,100. If you're using

200-step-per-revolution motors with 16x microstepping, one rotation is set at 3,200 steps. One full rotation usually drives a significant amount of filament into your extruder, so if you don't have any other advice about your extruder, try using a value of 200 for the first test.

- 3. Wrap a strip of tape or a sticker to the incoming filament about 50mm from the extruder's filament-entry hole.**
- 4. Measure the distance between the tape or sticker and the extruder body before and after the printer extrudes 20mm of filament, then write this number down.**

Suppose that you measure 48mm between the mark and the extruder body. The best way to measure this distance is to use a digital micrometer. (See Figure 15-24.) A digital micrometer can help you in many ways, including checking whether your printed parts come out as designed as well as measuring the filament diameter of different coils for setting in PrusaSlicer.

- 5. Extrude 20mm of plastic filament in 5mm steps, with a delay of a few seconds between steps.**

The delay ensures that the printer doesn't extrude too fast; it also reduces the risk that the motor will skip. You should have a smooth motion of filament driven into your hot-end and extruded.

- 6. Measure the new distance between the mark and the extruder as you did in Step 4.**

If your extruder is ideally calibrated, the new remaining distance (in this case) is 28mm. Chances are, however, that this new gap is either bigger or smaller than the 28mm you wanted. You may actually have measured 32mm, meaning that the extruder drove the filament only 16mm instead of the 20mm you expected. In Step 5 you clicked the Extrude button in Pronterface four times (20mm in total) so you should have had a 20mm movement of filament.

- 7. Calculate the steps-per-unit value.**

Use the existing number of extruder steps per unit in your firmware (which you set to 200 in Step 2), and the distance extruded (in this case, 20mm) to calculate the number of motor steps your firmware just moved. Because $200 \times 20 = 4,000$, this result is the number of motor steps your firmware moved for the 20mm of extruder motion you set. Because you achieved only 16mm of movement, however, you can calculate your actual steps-per-unit value by dividing that 4,000 by 16 to get 250.

You can make the same calculation if the number is higher than 20. It will be lower than the 200 steps you first tested.

8. Enter the new steps-per-unit value in the firmware.

If you enter the change in the extruder's steps-per-unit value in your firmware from 200 to 250, you should achieve the 20mm of movement you requested the next time you perform this operation.

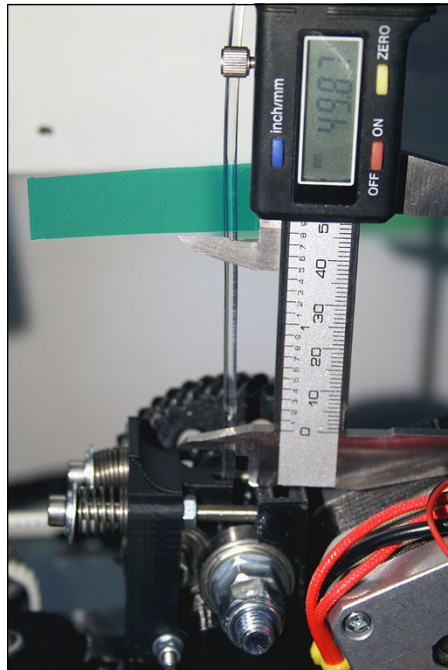


FIGURE 15-24:
Use a digital micrometer to measure the distance that the input filament moves when 20mm is extruded.

After updating your firmware with these changes, you're ready to print your first 3D object.

Printing Objects



REMEMBER

Make sure that your 3D printer hasn't been knocked out of alignment and that your hot-end is still a suitable distance from the build bed before you print. Fortunately, you don't need to calibrate the temperature of your hot-end and do extruder calibration every time you print; you've entered these values into your firmware and such settings don't require constant adjustment.

Now you're ready for your first 3D print. This moment is an exciting one, but don't get overly ambitious. Instead of printing a complex object at this stage, try

printing something easier, such as a simple cube. You can print cubes to test all sorts of things, including materials and settings; they're great ways to check things. Cubes don't take long to print and can show you how settings such as Infill and Solid Layers change the way that an object looks.

You can download a simple 20mm cube (20mm × 20mm and 20mm high) at www.youmagine.com/designs/calibration-set-for-3d-printers-extruders-and-materials.

To print your sample cube, follow these steps:

- 1. Load your cube object into PrusaSlicer.**
- 2. Set Infill at 20 (percent).**
- 3. Set three solid top and bottom layers.**
- 4. Export the Gcode and save it to the SD card of the 3D printer or load it into Pronterface if you wish to send it directly to your 3D printer via the USB connection.**

Pronterface shows the object loaded in the middle of the virtual print bed. (See Figure 15-25.) You can click the object and scroll through the various layers. In Figure 15-25, you see the base layer with a ring around it. This ring isn't part of the object being printed; PrusaSlicer adds it as the first part to be printed, to prime the plastic flow of the extruder before the object starts to print. The middle sections show the hexagonal infill and (finally) the solid top surfaces.

- 5. Set your print bed and hot-end to the required temperatures for the material you're printing and allow the printer to reach the correct temperature.**



TIP

Manually setting the 3D printer to pre-heat is usually a good idea. Pre-heating allows the machine to reach the correct temperature as well as balance any thermal expansion slowly before a print is started. If you forget to pre-heat, the Gcode does it for you before printing the model.

- 6. Manually extrude some material.**

Manually extruding material helps you check that everything is working correctly and homes the printer axis.

- 7. When the printer is at printing temperature, click Print.**

After a slight delay while the Gcode checks and stabilizes the temperatures, the print head moves to the middle and starts printing your cube — usually, with a gap-spaced outline to start the flow of plastic. While the first outline is being extruded, look to see whether the plastic is sticking; also make sure that the print head is neither scraping the surface nor too far away from it.

Figure 15-26 shows a well-bonded first layer. The printer has completed two perimeters. Notice the slight ridge; the infill looks solid and has similar ridges. For the first layer, you shouldn't see gaps between the individual extruded lines.

If you're not seeing a good bond of the plastic, stop the printer, and adjust your nozzle head a fraction closer. If material doesn't escape, and you see the flow stop and start, or if a lot of material squashes out (leaving very high ridges) and the nozzle is dragged through the plastic, the extruder is a little too close to the build bed. Move the nozzle head away.

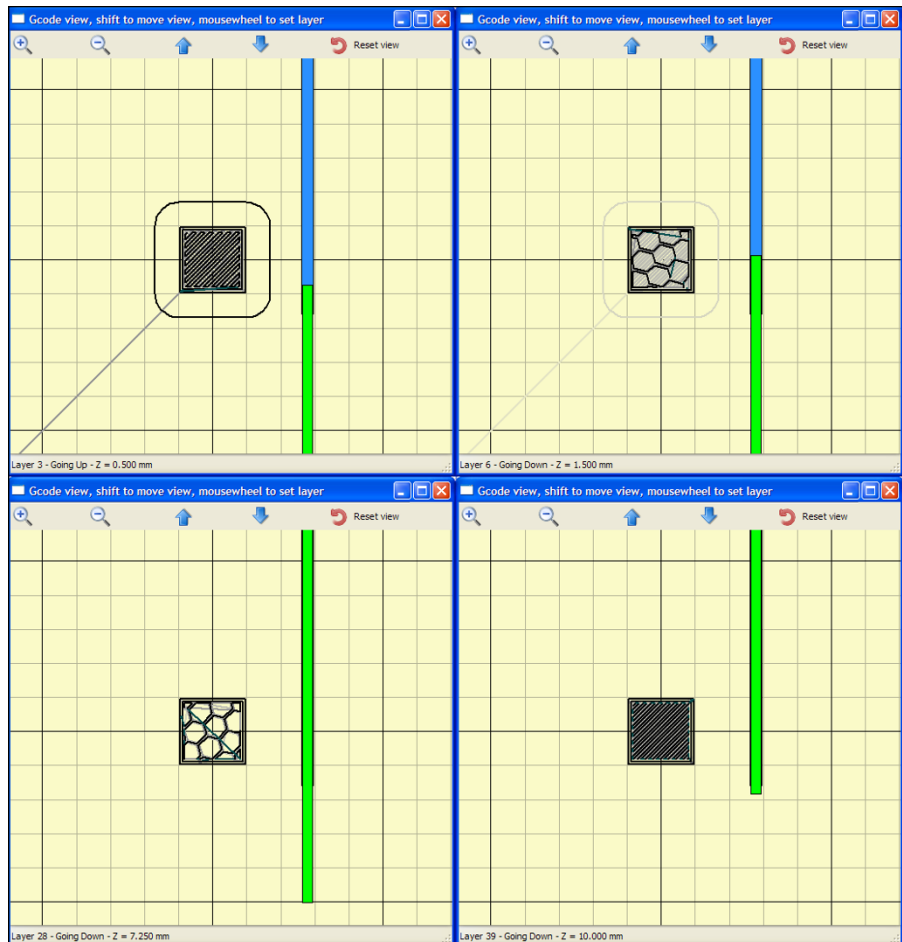


FIGURE 15-25:
Pronteface shows your cube loaded in the middle of the virtual print bed.

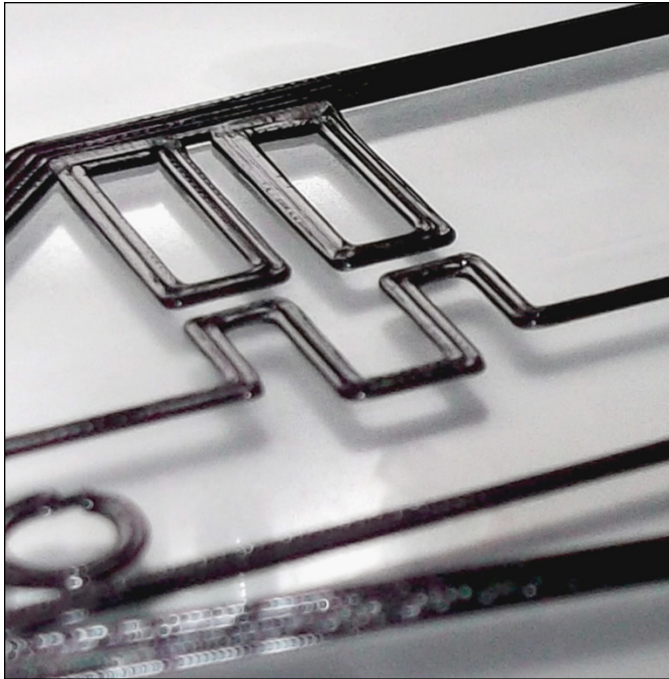


FIGURE 15-26:
A well-bonded
first layer.

8. When your cube is finished, confirm that it measures as close as possible to 20mm and 10mm high. (See Figure 15-27.)

If the cube printed significantly larger or smaller — at 40mm, for example — the `DEFAULT_AXIS_STEPS_PER_UNIT` value probably is set incorrectly for the Z and Y axes. Work out the new value by performing the same steps per millimeter calculation you used for calibrating the extruder extrusion distance in the “Calibrating extruder distance” section, earlier in this chapter. Make sure that you mark and remember the orientation of the cube when it’s printed. The distance from front to back of the cube on the build plate is the Y measurement, and the distance from left to right is the X axis.



TIP

9. Make sure that your cube’s corners have 90-degree right angles.

If not, make sure that your X-axis carriage is aligned straight across the moving Y axis.

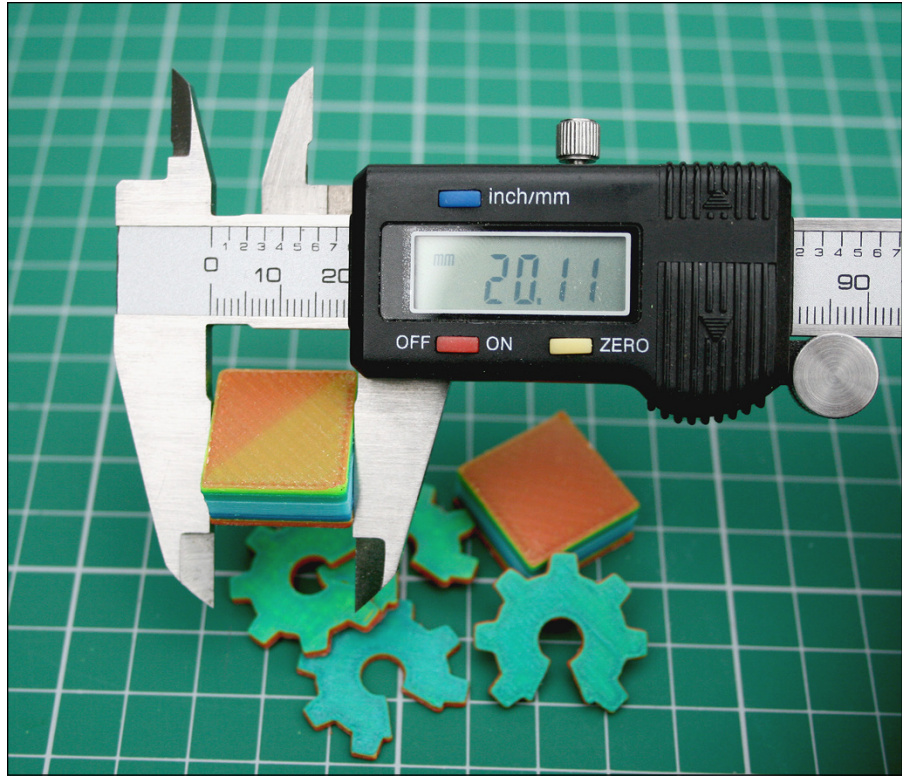


FIGURE 15-27:
Make sure that
your printed cube
measures
correctly.

Now you should be able to print more objects and explore the capabilities of your 3D printer. Learning the speeds, temperatures, and settings required to print different objects takes time. The best method is experimentation, because many factors influence 3D printers in various ways.

The next few sections describe a few tricks, tips, and PrusaSlicer settings for various types of 3D-model printing.

Printing vases, pots, and cups

Many models are intended to be printed as hollow. (For example, you want a finished cup, but it's designed as a cylinder; see Figure 15-28.) Such models are sealed at both ends and usually have details or patterns on the outside. They look solid but are intended to be printed as a single-wall-outline pot or vase. Such designs often produce the best surface quality but can be used only for single-walled objects.

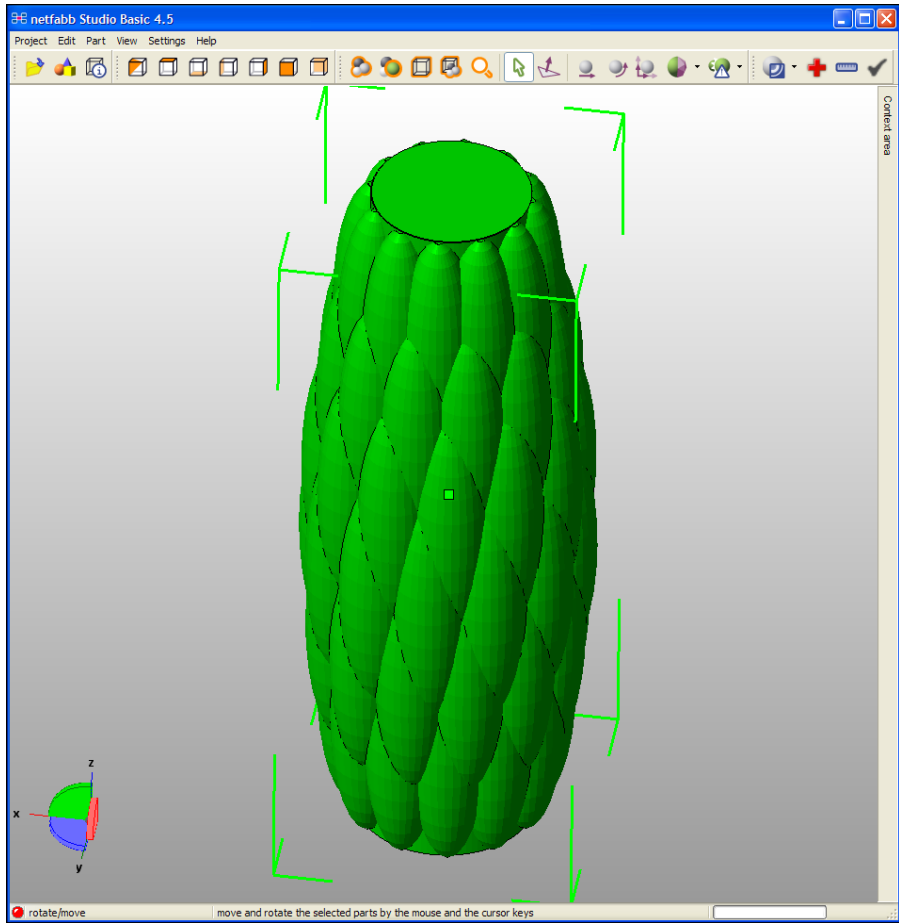


FIGURE 15-28:
A hollow-pot
design.

PrusaSlicer has a specific setting for cylindrical versions of such objects; it also allows for almost continuous printing without any extruder retractions or machine moves. This setting is called *Spiral Vase* (see Figure 15-29), which is available in advanced Expert mode. Set the layer height and number of solid bottom layers, and PrusaSlicer automatically removes the top layers, so you end up with a single-wall outline of the object and a solid base.

Even more impressive, after the solid base layers are printed, the single-wall outline is one single extrusion — usually spiraling around while the Z axis moves up ever so slightly as the print head rotates. All this movement makes printing much quicker, with no visible seams on the printed object because the extruder flow isn't stopped for a change of layer height.



TIP

Using a bigger nozzle is ideal for printing single-walled objects with the *Spiral Vase* setting. You can still select fine layers, but the wider nozzle provides a thicker single wall, giving your printed object more strength.



FIGURE 15-29:
The hollow-pot
3D model printed
as a Spiral Vase.
The vertical Z axis
never stops being
raised slowly,
resulting in a
seamless print.

Printing large single-piece objects

Printing certain objects — especially large single parts — can be tricky because the edges of a big part often curl during printing. Some parts are more likely to suffer from this problem than others. If you're printing parts larger than 100mm, even when using PLA on a heated bed (which doesn't allow much warping), you may still have some problems. Using ABS for big parts will certainly challenge most home 3D printers. Fortunately, PrusaSlicer has a setting that addresses this problem — and you may find the setting useful for other sorts of parts as well.

The Brim option in the Print Settings tab provides a horizontal ring of extending perimeters on the first layer of an object. This option can be highly useful if the object you're printing is sticking to the base of your build platform or if an object's corners start to warp during a print.



TIP

The Brim option was invented mainly to help big objects stick to the build plate during an extended print. It can also be helpful, or even essential, if you're printing tiny objects that don't have a lot of surface area in the first layer. The printed brim peels away from a finished object, with minimal cleanup required.

Printing tiny or highly detailed objects

When printing objects with molten thermoplastic, you have to allow for a minimum layer time for the material to be extruded and then cool enough to allow the next layer to be added. If you print each layer too quickly, you end up with a soft blob somewhat in the shape you intended, but without accurate features.



TIP

If you choose to print tiny objects, consider printing many of them together. By printing multiple smaller parts together the 3D printer can ensure it has a suitable minimum layer time because it spends a longer amount of time printing multiple parts, so each layer takes longer. This may sound like all you are doing is making your 3D print take a longer time to complete, and that's true, but you are also allowing each layer on each part to cool enough to accept more molten plastic on top. If you print just one small part, the slicer will slow down nozzle movements so the layer time is slower, but because the hot-end nozzle head is never too far away from the single part being printed, you may still not have enough time to cool the layer.

It's often better to end up with two or three small parts printed together. In fact, due to this minimum layer time requirement, printing multiple parts at the same time may take only slightly longer than printing a single part.



WARNING

Printing multiple parts at once has one downside: You may not want copies of a part, and you may start seeing tiny defects on the outside surface of an object where the head moves between the parts. These visual flaws may not be a problem for functional parts, but for a model intended for display, you probably require the best possible appearance.

To address the speed problem, you could slow the entire print speed, but there's a better option: Define a minimum print time per layer in PrusaSlicer. In Expert mode, choose Filament Settings and Cooling ⇨ Enable Auto Cooling. You'll probably find that this setting is a good one to keep enabled all the time. Read on to find out why.

When you define a minimum layer time, PrusaSlicer knows that it has to automatically calculate and slow any layer to this set speed. The result is that tiny objects automatically print slowly, and bigger parts automatically take longer than the minimum layer time and so are not slowed. Thus, the Auto Cooling setting gives you the best overall print speed and quality.

Automatic cooling is really important with some objects, such as pyramids. A pyramid starts with big layers at the base and prints faster as the layers get smaller toward the top. If you don't set a minimum layer time, the pyramid still looks great until the print reaches the top, where it's ruined by the very fast printing of tiny layers — which usually results in a blob of plastic instead of a defined, sharp peak. When you set a layer time of around 15 seconds, the print automatically slows as it gets closer to the top, and the model prints well.



TIP

You can print objects more quickly when you don't use the slowing-down method just described, but it takes some time to discern when this technique is appropriate. One way to achieve this result is to use a directional fan to force-cool the layers immediately after they print, but I recommend using this trick only for materials such PLA and for nonheated print beds. You can use 3M painter's tape to hold down PLA printed parts when not using a heated bed.

Printing many objects at the same time

As you get more confident with 3D printing, you'll want to set up a plate of parts and print them at the same time. This approach rarely causes problems, but you may want to use the nozzle-lift function (*Lift Z* setting) in the Printer Settings tab in PrusaSlicer. Raising the print nozzle a fraction before a travel move is a good idea when you have a lot of parts on a build surface. This technique can reduce the chance that the printer will accidentally knock off a part or shift the print carriage out of alignment.



TIP

For some objects and 3D printers, you may find that rotating a part 45 degrees on the platform makes printing easier, reduces warping, and minimizes the possibility of travel moves that hit corners or the edges of parts. If a print fails or has problems, either perform this simple rotation or reposition the object on the bed before changing other settings.

Improving print quality

As a general rule, slowing print speed improves print quality. Fast travel speed can affect print quality because the print head gets to a new point quickly, and the high acceleration and deceleration sometimes cause unwanted shadows and artifacts on the print. Experiment with machine travel speed before changing other settings.

Temperature also plays an important role in print quality and is especially linked to print speed and layer height. As a general rule, if you start to slow your printing speed below 20mm per second, you should also reduce your printing temperature.

You may decide to print more slowly for a variety of reasons, such as printing a single small object or a part that's been tricky to print in the past. Most thermoplastic materials print perfectly well at temperatures lower than you'd normally use. Reducing the temperature also helps stop hot plastic from oozing out of the extruder nozzle, which can make a big difference in the quality of fine parts being printed slowly. You have more control of the plastic being extruded with such an approach. Also, you lower pressure in the extruder nozzle, which further improves print quality.

If you're getting lots of print failures when you print plates of multiple parts, you may have a small mechanical-alignment problem. Check your belts to see whether they're tight enough. Also check carriage speed. If you're moving the carriage too quickly for the frame design of your 3D printer, try slowing it. If that change doesn't help, consider tweaking another Expert-mode setting in PrusaSlicer: Avoid Crossing Perimeters. This option tries to move the print head around the outside of a printed layer instead of across the part to reach the other side of the build bed or other object. The setting extends the time required to print an object, but it also improves the quality and reliability of the print.



TIP

PLA prints at temperatures as low as 160° C when you're printing parts slowly, which can produce less oozing and improve finer detail for smaller parts. You can still use a fan to force-cool the plastic layers, even at such low temperatures.

Identifying Machine Problems When Print Jobs Fail

If your 3D printer has been working fine and but starts to develop print problems, failed model prints, or a constant failure of extrusion or lower quality output, check to see if you can use the print failures as a guide to see if a mechanical aspect of the machine has failed or as a way to identify which components may need replacing or servicing.

The example in Figure 15-30 shows what can happen to a 3D print when the linear bearings wear down and start to stick on the smooth rods during the 3D-print process. The mess you see in the figure could also be an indication of over-extrusion, where too much material is extruded. (This can happen when the extruder is not correctly calibrated or the filament size is not set correctly in

Prusa-Slicer.) If this was your first print and it failed, then explore your Slicing settings, material calibration, and print speed. However, if this was a model you have printed successfully before or maybe as part of a print farm that has printed multiple times without a problem and you then see a failure like this, start to suspect that a mechanical failure or a worn component may be the cause of the problem. It's all too easy to ignore an occasional print failure and assume something went wrong with the settings when it could be that a worn component needs replacing or that the 3D printer needs servicing.

If you think you may need to replace the linear bearings, you'll discover it's relatively easy to disassemble the carriage and remove the worn bearings. (See Figure 15-31.) But don't stop with just the worn ones. After taking the trouble to disassemble the carriage and remove any worn bearings from an axis, it's a very good idea to replace all the bearings at the same time. (See Figure 15-32.) If you only replace a single bearing, the others may still be worn and can quickly cause a failure again.

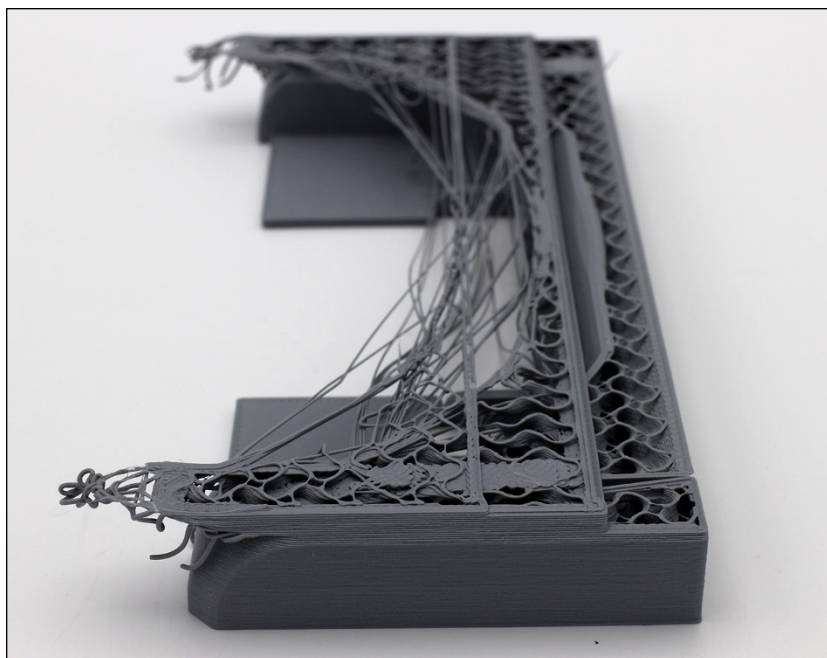
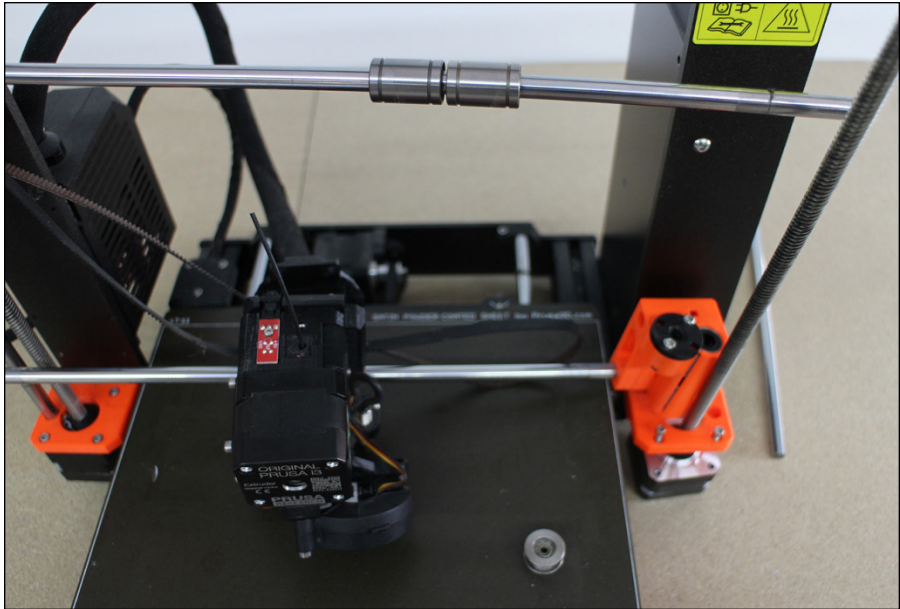


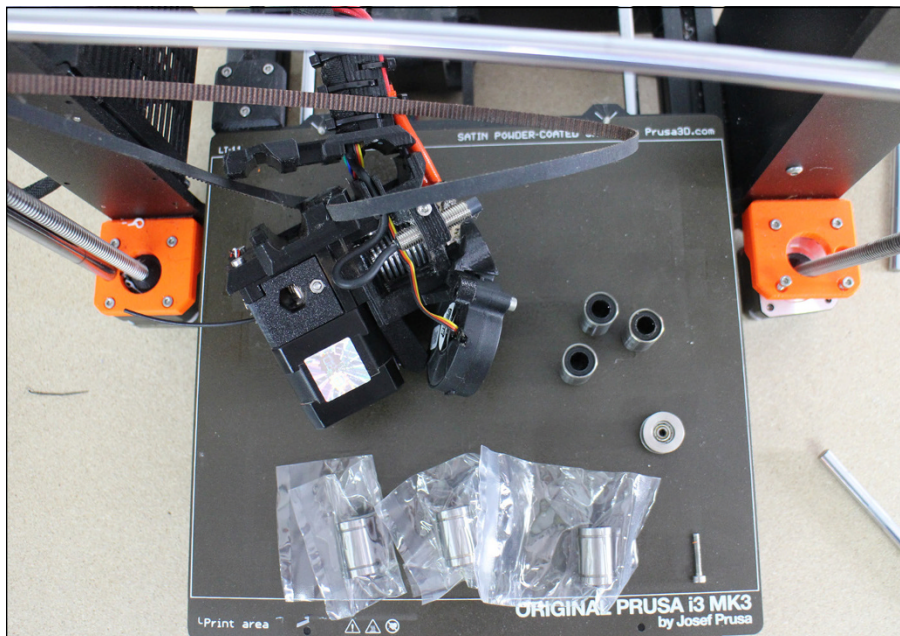
FIGURE 15-30:
A failed 3D print may indicate that the motion of one or more axes may be sticking.

FIGURE 15-31:
The X carriage
removed from
the smooth rods
and failed LM8UU
linear bearings to
replace.



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FIGURE 15-32:
The X carriage
bearings
removed ready
for replacement.



Prusa Research a.s.

Improving Print Speed

Lower print speeds and higher quality often go hand-in-hand. Most 3D printers will have a maximum speed for non-printing travel movements, limited by the mechanical construction and quality of the motion components and control system used. There is often not all that much you can do to speed up the printer, and the print process will always go much slower than the machine can handle. Therefore, when it comes to increasing print speeds you are limited to many of the things I have already discussed, such as the size of nozzle and layer height, when you want to affect the overall time taken to print out a particular model. The overall deposition rate of how much material you can melt and extrude also very much depends on the type of nozzle heater and the hot-end design.

Some 3D-printing extrusion systems are designed to deposit more material by having higher capacity heaters and more powerful extruder motors that are capable of pushing out more melted plastic. These systems really only work well with larger sized nozzles, which most often reduce the level of fine details on the print surface. Great if you want to print out a full-sized table, not so great if you want to print out a detailed model of a small frog.

Another trick to improve overall print time is to print out more than one copy of a part at the same time. If you choose to print each single part one at a time, Prusa-Slicer will often automatically slow down to a minimum layer time to ensure the previous layer has had time to cool before the next is started. When you print multiple parts or an entire plate filled with parts, the print time will obviously be much longer, but as an overall total print time, this method will often be much quicker than printing single parts one after another.

Another trick for speeding up print time is to change the extrusion width in Prusa-Slicer. Doing so forces out more material to be a wider printed trace. The Prusa-Slicer will automatically calculate the volume needed to make a wider width extrusion, so you don't need to worry about that aspect. You can also do this with any sized nozzle. If, for example, you have a 0.4mm nozzle, you would normally use an extrusion width of around 0.45mm, but if you change this to be 0.6mm you will get some of the same benefits in speed that you would see by physically changing the nozzle size.



WARNING

Changing the extrusion width does come with some dangers. One potential issue could arise in which an overhanging perimeter or filament bridge will not act as nicely as a true 0.6mm nozzle or if your settings were set to the normal ~0.45mm size.

It's worth experimenting a bit with your nozzle extrusion width in PrusaSlicer as this can be quite a handy feature if you need to speed up a model and you do not wish to replace the nozzle.

This tip can also work the other way around. For example, you can set an extrusion width of a 0.4mm nozzle to be 0.3mm. Doing so is sure to increase print time, but the final print quality will often be much improved.



REMEMBER

If you do try this method of changing the extrusion width to be wider or thinner than your actual nozzle in PrusaSlicer, do not specify a setting higher than 150 percent or less than 50 percent of the nozzle size fitted. If you go over these limits, the tip of the nozzle will no longer be able to control the flow of material by smoothing it out.

IN THIS CHAPTER

- » Getting productive with 3D printing
- » Refining the printing process
- » Making 3D printing practical
- » Designing for 3D printing
- » Postprocessing, recycling, and finishing
- » Printing big objects
- » Home filament extrusion
- » Sustainability and Masterspool
- » Introducing innovations in 3D printing

Chapter **16**

Refining the Design and 3D-Printing Process

After you've built or bought your first 3D printer and calibrated and printed your first few objects, what's next? In this chapter, I show you how you can ensure that you are getting the best results from your 3D printer. I'll also have you consider some practical uses for everyday 3D printing at home and offer some guidance on designing parts for the 3D-printing process.

Being Productive with 3D Printing

3D printing is more accessible to more people, but being accessible isn't the same as being usable or user-friendly. As the fundamental technology matures and also reaches speed and material limitations, more innovative processes will be developed to be safer, quicker, and easier for the average user to manage.

In recent years we have seen a steady increase in the automatic setup of a 3D printer, from automatic bed leveling to filament sensors that can inform you when you are at the end of a spool or if the filament has jammed. Some 3D printers now have even more enhanced usability, with touch-screen interfaces and a selection of easy-to-use menus for setting up your machine.

Now, the reality check: These changes aren't going to happen all that soon. Manufacturing free-form objects on demand isn't easy, and atomic replication of objects isn't even on the horizon. Even metal 3D printers are still used only in industry due to complex safety systems and requirements.

3D-object repository sites such as Youmagine (www.youmagine.com, see Figure 16-1) provide access to thousands of ready-to-print objects, but you have a limited number of ways to change or repurpose the objects on these sites without delving into 3D design. Some 3D models or programs have some customizable features, enabling you to add a name or tweak the size and shape of the object. More often, though, to make significant changes, you need to edit the 3D model directly, which can be an obstacle to adoption of 3D printing for some people who don't have experience in 3D design.

To combat this problem, companies and manufacturers are adding a more user-friendly experience in the form of ready-made material profiles, automatic setting generators (see Figure 16-2), and intelligent 3D-model analysis systems that suggest better ways to print your object. These changes are taking away much of the guesswork and experimentation required to achieve a successful 3D print. You can't yet click Print and be sure that an object comes out as you expect every time, but that day is getting closer all the time.

For 3D printing to be widely adopted at the consumer level, designing 3D objects will have to be easier. Companies such as Autodesk and Adobe have spent decades refining and simplifying the 3D design process for both professionals and novice users, and the process is improving all the time. Innovative tablet-based apps, for example, allow organic design and manipulation of 3D designs by touch and gesture.

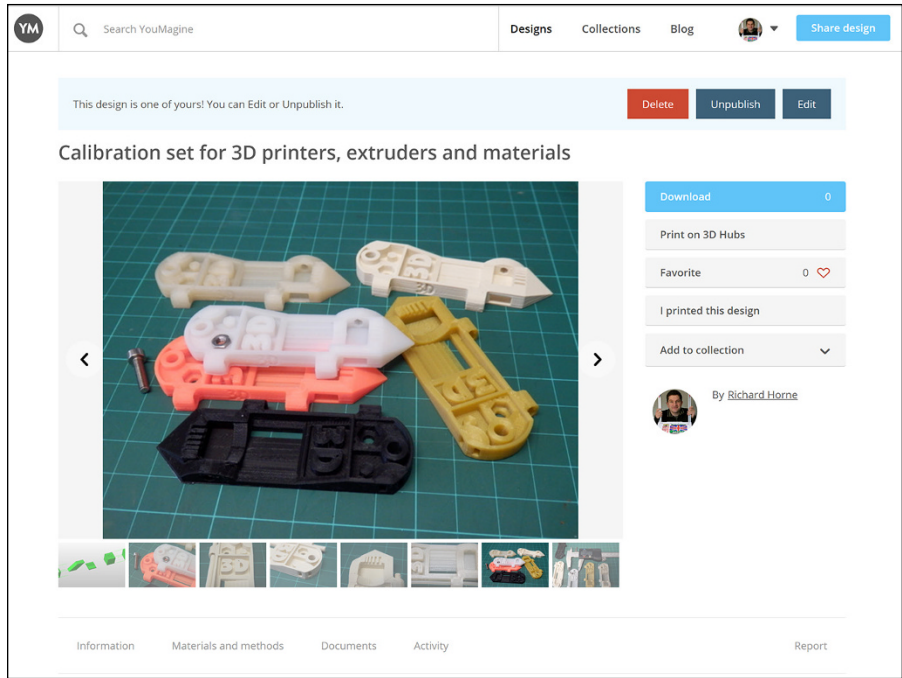


FIGURE 16-1:
The 3D-model sharing website YouMagine.

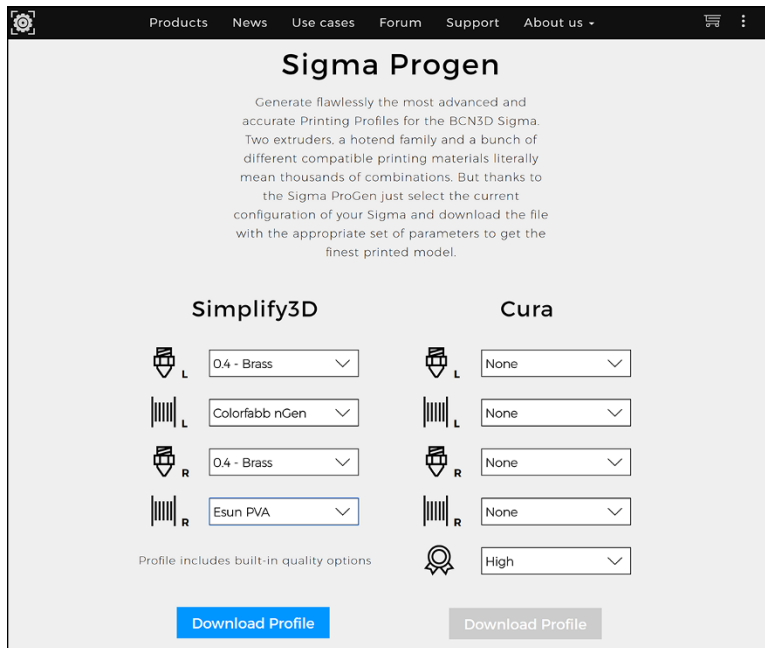


FIGURE 16-2:
The automatic profile generator for the Sigma 3D printer.

Refining Your Print Preparations

After you've bought or built a desktop 3D printer, what more do you need to do before you dive into 3D printing?

The next few sections discuss some further steps you can take to ensure that your 3D printer is correctly set up and calibrated, including some simple models you can use to refine the material deposition system so that parts fit and are accurately reproduced. I will focus on FDM filament 3D printers here, but many of these tips and advice are also applicable for resin-based SLA 3D printing.

Before you make your first attempt at printing, make sure that the machine is set up correctly — not damaged or out of alignment. Check that the electronics, motors, and sensing stops are operating correctly. Then gather the basic information you need to complete your first 3D print.

In the previous few chapters, I cover many of the calibration, setup, tuning, and maintenance required for everyday 3D printing. Below you'll find a short reminder list and some top tips for getting the best out of your 3D printer and materials:

» **Level the build platform and set the first layer distance correctly.** A level platform and the correct distance are two of the most important aspects of successful 3D printing. Just because you have a bed-sensing probe or automatic level system, don't expect it to work correctly right out of the box or after you assemble the kit. It's almost always essential that you manually check and set the offset distance from the probe sensor and the nozzle of the hot-end.

Like many recent desktop 3D printers, the Prusa MINI has a dedicated calibration sensor for detecting the distance between the nozzle tip and the build platform. You can perform the automatic first layer calibration procedure as many times as you require to refine and tune-in the correct distance. Although this procedure runs automatically, in order to compensate for an out-of-level build platform you will need to monitor the calibration pattern being printed and rotate the control knob to raise or lower the nozzle until you have a line of extruded material that is squashed into an oval shape. The on-screen instructions will help you follow the first layer calibration procedure until it matches the 3D printer's examples in the manual.

The sensor triggers at a set distance from the build platform, but the tip of the hot-end nozzle usually is slightly farther away than this trigger point. Therefore, you need to set a Z-axis offset. Usually, you have a setting on the machine that controls the offset of the nozzle from the build platform. Often you place a sheet of paper onto the build platform and adjust the nozzle up and down, by rotating the control knob on the 3D printer. When this distance

is correctly set, a high-quality bed sensor probe (capacitive, inductive, or infrared) should give you highly repeatable results time and time again. If you have a mechanical sensor such as a micro-switch, you may not achieve repeatable results time after time. As I mention elsewhere in this book, it's worth your while to make sure that a good quality bed sensor probe is a feature of your 3D printer.

At the start of a 3D print, the sensor checks the platform distance and then moves the extra offset (usually, -0.5mm to -3mm) before starting to print the first layer. Tuning this offset distance and making sure that the build platform is level and flat gives you perfect first-layer results and a greater chance of print success.

- » **Make sure that the correct level of power is being fed into the stepper motors driving the motion of the 3D printer.** Verifying the power level ensures that the stepper motors don't lose steps at higher speeds and don't overheat.



REMEMBER



TIP

Too much power is as bad as not enough. If the power level is set incorrectly, your 3D printer may never operate properly, or it will fail often during printing.

You usually adjust motor power on the stepper-motor drivers by rotating a small dial called a *potentiometer*. Many kits come already set to the correct setting, but just as many require you to perform this step. Many more 3D printers now achieve this from the user interface menu. Check with your particular model of 3D printer to see whether it's automatic or allows you to tweak the motor power within a set range for your machine.

The exact level of power depends both on the motor you're using and the type of driver installed in the electronics system. Check with the manufacturer to find out what settings you require for the stepper motor's current (power) limit.



TIP

The extruder stepper motor requires a current limit to be set, and this limit may be higher than the limits for the motors used for X, Y, and Z motion. Some electronics control systems can set the motor power via firmware settings you can change on the control panel menu of your 3D printer. Check to see whether your machine can be adjusted through the menu, which is usually much more convenient than having to adjust settings in the firmware code that you then need to recompile and upload to the 3D printer. Also note that some 3D printers now use this current limit as a method of detecting that the carriage has bumped into the end of travel. The increase in power in the motor indicates that the carriage has reached its limit of motion. This is still called an *end-stop signal*, harking back to the days when 3D printers had a mechanical switch that the carriage bumped into, thus triggering the "end-stop." Mechanical switches tended to wear out or be damaged, so detecting a short spike in power of each motor (current limit) is a much better method for detecting end of travel.

» **Check the extruder calibration.** Set the important extruder steps (eSteps) per unit (unit being 1 millimeter) to ensure that the correct amount of plastic material is pushed into the hot-end. The Slicing program uses the eSteps number to calculate the exact flow of material being extruded for the required print move to ensure plastic is not over- or under-extruded into the model being printed. (Chapter 15 has instructions on how to check — and also update — the eSteps setting.) If you can't easily change the number of eSteps that your extruder motor is set to, you can also adjust the extruder multiplier, usually from around 95 percent to 105 percent; this will also help adjust for undersized or oversized filament and worn mechanical parts. Lastly for extruder flow, you can often also adjust the extruder flow on the 3D printer itself. This can do the same finetuning job for slightly too much or too little material being extruded. Being able to do this while the machine is running is useful and can often reduce the need to reslice an entire model just because a filament has slightly different dimensions from the last spool you used.



TIP

You'll often see the term *print move* and *travel move* being mentioned in slicing settings. These terms describe particular motions of the printer. A *print move* occurs when plastic is being extruded out of the nozzle — a *travel move* is any machine movement when plastic is not being extruded. Travel moves are almost always many times faster than any print movement.

» **Check that the temperatures you set for the hot-end nozzle and the build platform are correct.** Making sure that the temperature you set for a plastic material is the same as the temperature you set for the hot-end is really important, because you really don't want to be melting plastic at the wrong temperature. When the temperature is too low, you risk jamming the nozzle or the extruder system. When the temperature is too high, the material can begin to break down — or, in a worst-case scenario, release gases or catch on fire, causing significant damage.



TIP

You can check the temperature in several ways, but using a handheld temperature sensor is the easiest way. The best sensor for the job is a physical probe that can make direct contact with the nozzle and the heated build platform. (Infrared and laser sensors don't work as well.)



WARNING

The most important piece of advice I can offer you is this: Never leave a 3D printer unattended. Don't run them overnight while you sleep; don't leave them running while you pop out to the shops. Make sure that you have operational smoke alarms near your work area. Also ensure that you have adequate ventilation or fume extraction. If you have any doubts about the printer setup, check with the manufacturer. A 3D printer by its very nature is often a piece of very hot, moving machinery, and you must treat it with respect.

After you've checked and double-checked your printer, you can get ready to print a model. Many manufacturers supply machine profiles and material settings for the slicing program being used for model print preparation. Make sure that you have the correct profile installed; after that, see whether you require any firmware updates that the manufacturer has issued since you bought the 3D printer.



TIP

It's very tempting to print off something impressive, but to be on the safe side it's best to start with a basic 20mm cube or some other small part, like the ones shown in Figure 16-3; something small is better suited for assisting you with the initial calibration of the printer.

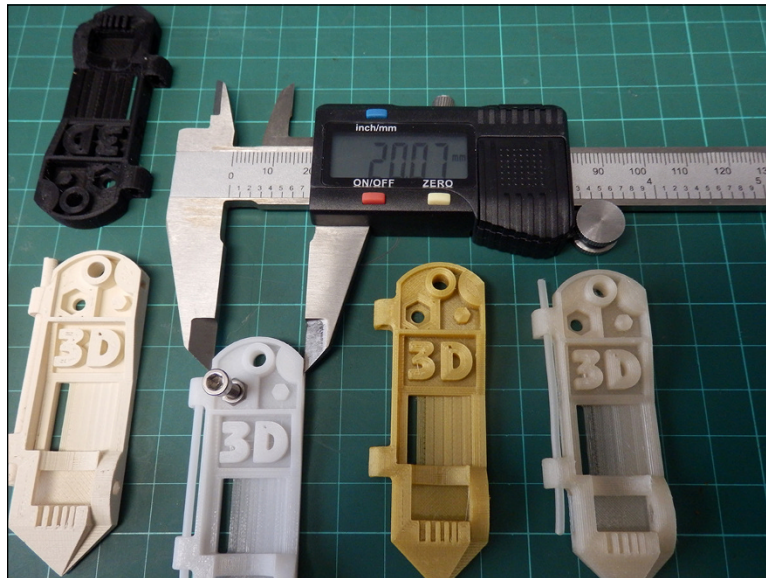


FIGURE 16-3: Printing a number of calibration models helps you refine settings for different materials and nozzle sizes.

A 20mm cube should take around 10 to 20 minutes to print; producing it can really give you the confidence to know the machine is set up accurately, the X-, Y-, and Z-axes are aligned, and material flow is correct. You will get tired of printing cubes but remember that if you spend some time calibrating now, anything else you print is much more likely to be successful and also dimensionally accurate.



TIP

You can download a simple set of 20mm calibration cubes from YouMagine at www.youmagine.com/designs/calibration-set-for-3d-printers-extruders-and-materials.

Examining a Design Example

In this section, I discuss how to design a 3D object as a fully functional part, not a model or prototype. I'll walk you through the key design steps and fill you in on which materials are best to use.

For this first example, I designed a small filament spool rack mounting hook. (See Figure 16-4.) Using FreeCAD, I came up with a hook design that would let you mount multiple spools behind a Prusa i3 MK2 3D printer. The goal was to allow a standard 15mm wooden dowel to be used with 3D-printed custom filament spool adapters so that a wide range of materials could be mounted, thereby facilitating rapid switches from one spool to another.

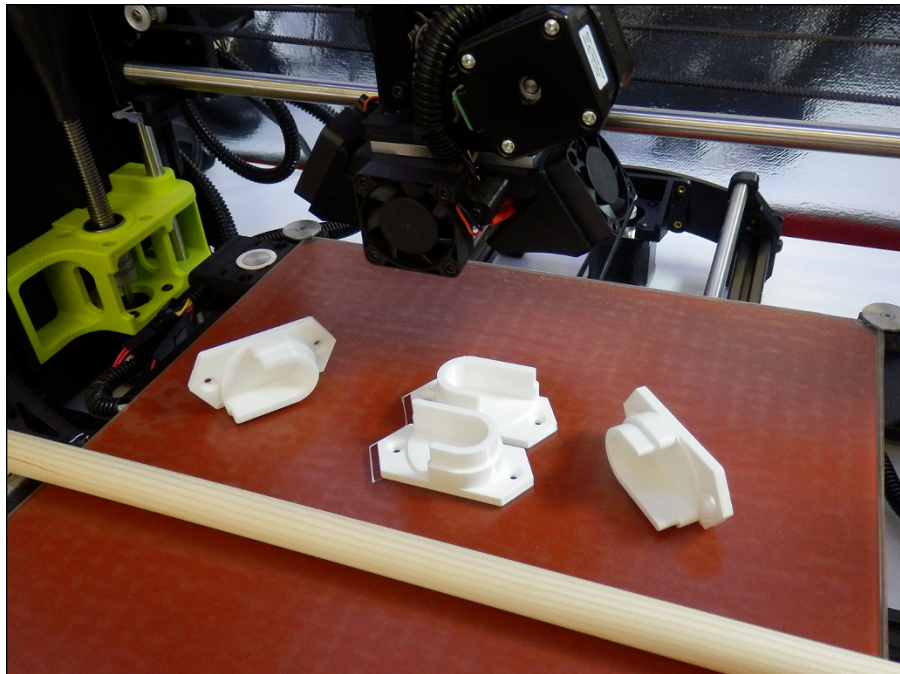


FIGURE 16-4:
Several printed
spool mounts.



TIP

You can download a file for this model, as well as other mounting brackets, from YouMagine at <https://www.youmagine.com/designs/filament-spool-holder-brackets-and-adapters>.

When designing and printing this part, consider how much weight it's likely to be supporting. For the purposes of our example, the span from one side to the other is around 80cm, so about nine spools can fit in that space. Normal filament spools

weigh about 750g to 1kg each. I assumed a maximum load of 6kg for the printed plastic and fixings because the wooden dowel would start bending at weights higher than this loading. (See Figure 16-5.)

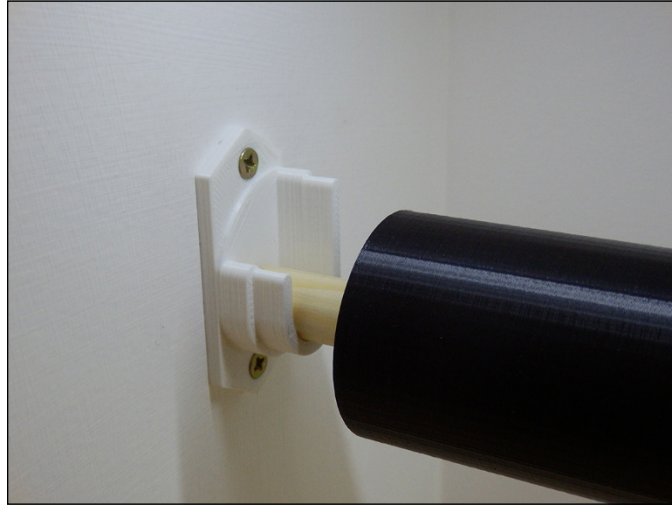


FIGURE 16-5:
The simple
mounts created
for this example.

This mount will be attached to the wall with countersunk wood screws — two on each side should be adequate — but you could add more if you want to support more weight. In that case, you'd also need a thicker wooden dowel.

The back fixing plate needs to be at least 3.5mm thick, and the outline of the U-shape wooden dowel holder protrusion needs added material because the 3D-printed layering process will be a weakness. If not adequate, the printed plastic will be an obvious break point because the layered manufacturing method is not as strong as a solid injection molded part of the same thickness.

For this reason, the cup for holding the dowel has a wider ring around the base to create a stronger, more solid protrusion. The top section of the U-shape cup enables easier positioning of the dowel into the 3D-printed wall bracket, as the dowel will be shorter than the span across the two mounts. You don't want one end of the dowel to slip out of the mount because the cup doesn't extend out enough when you lift the opposite end. You could mount or design these holders in a line if you need to raise and lower the height of the spools, especially if you use wider- or smaller-diameter filament spools.

The screws are aligned with the top and bottom points of the base. This allows you to draw a pencil line on the wall or surface and line up the top and bottom of the mount so everything stays vertically straight. Then it's just a matter of printing the mount with a suitable material and infill strength.



TIP

When you make functional parts, think about how they'll be used. Adding alignment features or small marks can help users with installing things straight or in line with other parts. In this example, I made the top and bottom of the wall mounting bracket design into a point. (See Figure 16-6.) You can align the top and bottom points to a pencil mark on the wall to ensure the mount is vertically straight.



REMEMBER

In 3D printing, you can add complexity or customization as you need it. You can design exactly what you need.

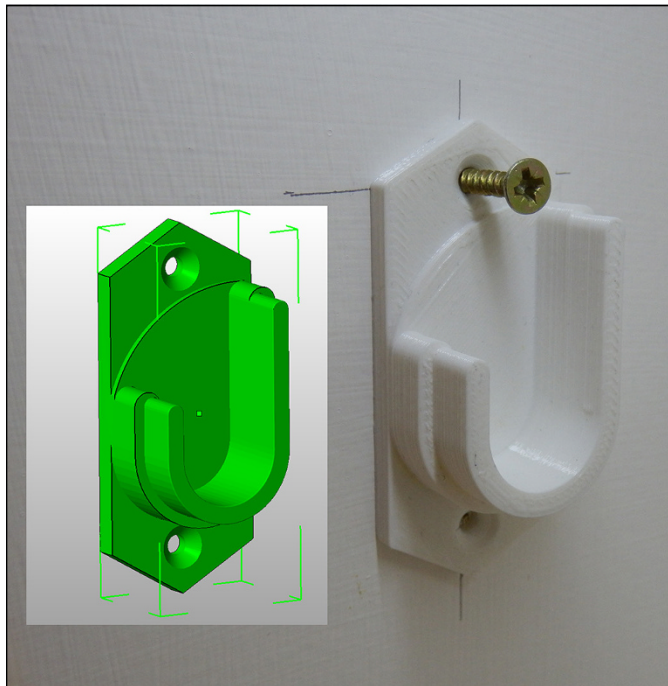


FIGURE 16-6: Using 3D design to assist with installing a product.

AN OBSTACLE TO 3D PRINTING

One complication that many people run into when designing items for 3D printing is understanding the properties of the materials they're working with. You need to be able to gauge the weight, stress, and loads that will be placed on an object if you plan to use a desktop 3D printer to manufacture useful items or make repairs. Unfortunately, there's no quick fix for this problem. 3D scanners can't make the job easier because they evaluate only the outside surface of an object. Whatever you scan always needs further manipulating or combining of multiple scans of the 3D model before you can print.

Making this process easier for the average user will take some combined effort from materials manufacturers, machine designers, and the software designers who produce 3D models. Unfortunately, 3D model files rarely include useful data about the materials needed to do the job. The file simply defines an outline 3D surface; you have to decide how to print by using the hundreds of user-modifiable settings in a slicing program — a daunting problem for many users. You can follow some general rules with infill values, perimeters, and solid top and bottom layers. In the following pages I highlight a number of these slicing settings to help make you familiar and confident to try out some further practical 3D printing ideas.

Practical 3D Printing: Looking at Five Quick Examples of Practical 3D Printing at Home

Not everything should be 3D-printed. Just because you have a 3D printer doesn't mean you can always use this tool to produce the things you may need. That said, if you are designing the parts yourself, then you have a significantly better chance of making something that is appropriate for the 3D-printing process. In the following sections I show you a few examples of appropriate and practical 3D-print design and models and also how to estimate what settings you may require for a functional finished physical design.



REMEMBER

There will always be a use for a 3D-printed concept model, something to hold and feel, but when we start to talk about using 3D printers for production, repairs, and replacement of parts that may have been produced from alternative materials, you also need to consider if a 3D printer is actually the right tool for the job. A laser cutter, CNC machined part, or cast model may well be more appropriate.

One of the best aspects of 3D printing is that you can manufacture multiple models without the need for any tooling and, if you change something, you don't have to pay any tooling costs to make further modifications or waste time waiting for samples before you can even start production. For these reasons alone, 3D printing has long been selected as a default process for prototype models and physical concepts. As the prices for various materials have lowered and the cost of 3D printers has decreased and their speed has increased, it's now very viable to design parts for 3D print manufacture and use on a large scale.

Using my 3D printers, I have made countless repairs, upgrades, and useful devices you just can't buy and time-saving tools to help me build or design something. A 3D printer really is a useful device for practical solutions around the home, as Figure 16-7 makes clear. All of these were designed and printed during the lockdown of the global Covid-19 pandemic. It was not easy to get to the shops, and I had time to do some DIY around the house. Instead of buying items, I made my own. Figures 16-7 through 16-10 illustrate four quick examples, which hopefully will get you thinking about some of the things you can do on your own.

One day, I decided I needed a water filter for my fishpond. The design I came up with uses a simple plastic box and some pond filter pads along with a few 3D-printed parts to make a combined pond filter and waterfall. (See Figure 16-7.) The fish love it, and it's still in perfect condition almost three years later.

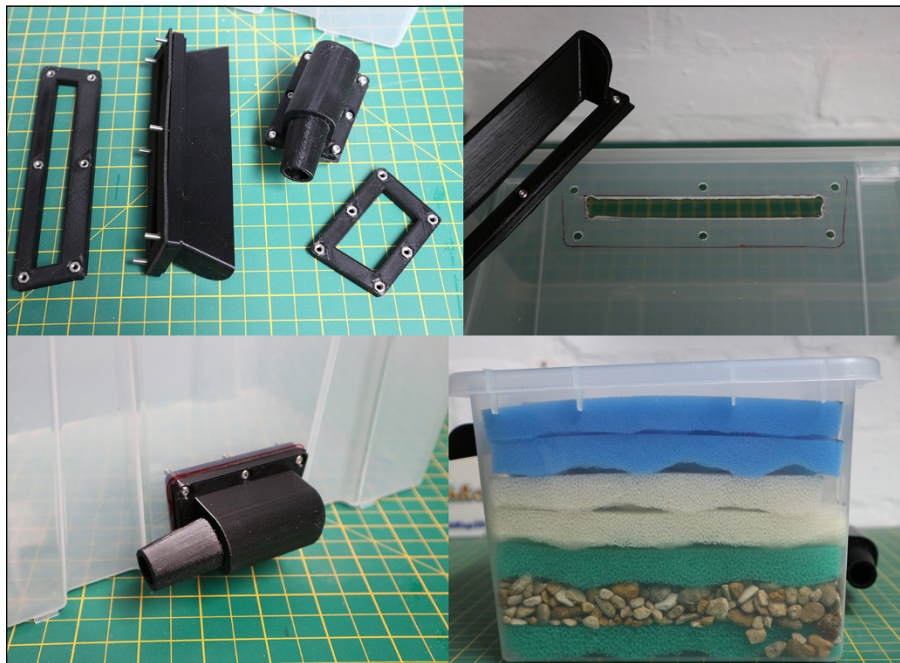


FIGURE 16-7:
3D-printed parts
for a DIY pond
filter.

I installed new fence posts but could not get hold of nice-looking end post caps, so I printed my own. (See Figure 16-8.)



FIGURE 16-8: Custom size and shape end post caps printed in marble PLA will last for years.

A TV that had previously been wall mounted had its legs removed and required a 3D-printed table mount. (See Figure 16-9.) Simple, practical, and strong — and all of it printed in PETG.

My design for the 3D-printed electronics box (shown in Figure 16-10) made making the box easy to put together a priority. The design uses brass threaded inserts that are melted into undersized holes. The 3D-printed material then melts around the brass insert, making a solid fixing point for small bolts. The result is a clean finished box with discrete fixings.

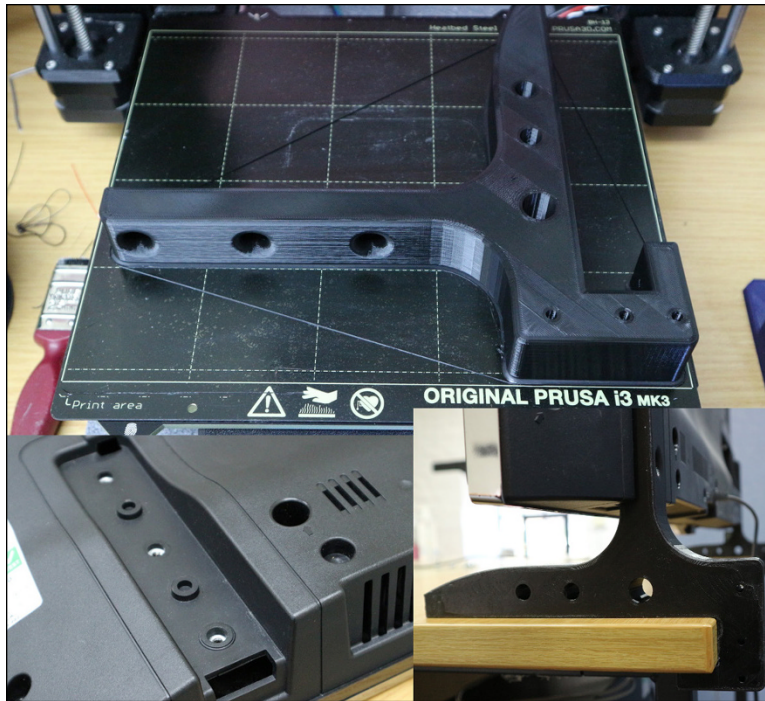


FIGURE 16-9:
A wall-mounted TV needed to be desk mounted.

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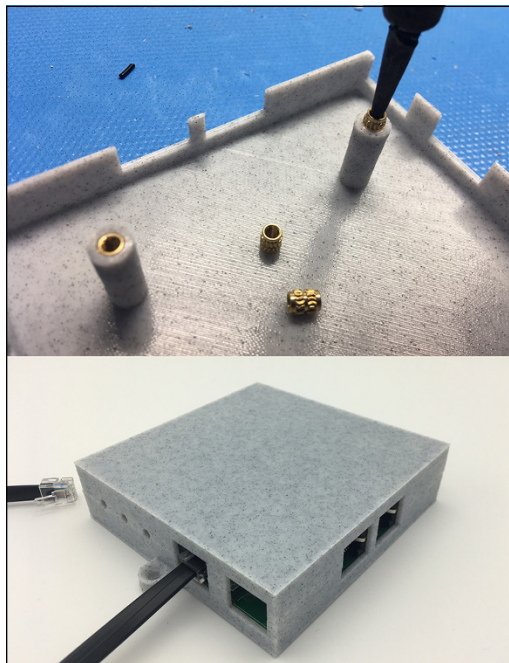


FIGURE 16-10:
A 3D-printed electronics enclosure using brass heat inserts.

Designing Parts for 3D Printing

3D-printed parts intended for practical use need to be designed for both the application and the printing process you're using. In this section, you get a chance to look at the design aspects and print settings of the spool mounting bracket example I introduced in the previous section. I'll also fill you in on what kinds of materials are appropriate to use for this bracket and similar objects.

As you design a part, include the suggested material type, color, infill level, orientation, and finishing method in the 3D design file so that the machine can read these criteria and advise the user what material to load. Better still, work with a printer that can automatically fill in settings for processing to ensure a strong or correctly orientated part for manufacture. The adoption and use of new additive manufacturing types like AMF (additive manufacturing format) will allow all these things — multiple parts, multiple materials, the color of object parts, and the density of fill levels — to be defined.



REMEMBER

AMF is not commonly used for desktop 3D printers. At this point, only a few industrial machines are using the AMF format, but that is likely to change as more emphasis is required on the design-to-3D printing process for even desktop machines.

As I have mentioned a number of times already in this book, plastic materials used in 3D printing can range from very hard and brittle to incredibly elastic, soft, and stretchy. The material you use depends on the purpose of the item you're printing.

Some 3D printers give you even more flexibility by allowing you to also mix multiple different materials to make some sections stiff and others flexible. If you expect these materials to also bond together with each other, you will need to follow the advice of the manufacturer or select materials from the same family or range. You can also select materials that purposefully do not wish to bond together; these can perform support structures that can break away after printing. The more you experiment with material properties, the more confident you will become with appropriate use.



REMEMBER

The more you understand about the properties of various filament materials — both straight off the roll and as used in simple test objects — the more successful your printing experiences will be. Bending and snapping a length of filament can tell you a lot about how the material will react to impact and load or stress. Sometimes, destroying printed parts helps you understand more about the limits of a particular material.

Adding layer upon layer of semi-molten plastic can create a weak point, and if the extruding temperatures of your hot-end were too low for a material, you may get

poor layer bonding strength, but you can't always know until you've experienced those situations. Experimentation and research are necessary before you try to produce a usable item.



TIP

Printing single-walled objects such as tubes and cylinders along with fully filled 100 percent solid plates can help you gauge how strong a material will be after 3D printing. You may need to crush, twist, or drop a part to find out some of the material's properties, such as layer adhesion strength.



WARNING

Safety first! If you've ever snapped a single strand of round spaghetti, you've noticed that almost every time, a small section breaks off and flies across the room. The same can be true of filaments or 3D-printed parts. Be very careful when removing parts from your build platform. If you decide to do some strength testing of various plastic filaments or destruction testing of any printed parts, take care. Always wear safety glasses and gloves for protection.

Material

For the spool mounting bracket, you have plenty of options when it comes to materials. Because the spool bracket needs to be stiff and able to take a few knocks and bumps while in use, I decided to use a co-polyester for this part because it offers a good overall range of properties for a mechanical, functional object like this bracket. Following are some of the plastics I considered for this model before making my final choice:

» **Polylactic acid (PLA):** This material is routinely used to print functional parts of 3D-printer kits. It's rigid, has good layer bonding, and is ideal for printing parts larger than 100mm because it has a low tendency to warp or deform during printing.

PLA, however, isn't as impact-resistant as some other plastic materials and can crack under excessive loads or knocks. Also, due to its low-temperature glass transition point (around 55 ° C), it can creep (slightly deform) over time, especially when a fastener, like a screw or bolt, is used to compress or pull on the printed layers of a PLA object. I have seen people use PLA to make a wall mount TV bracket; it works fine for a few weeks, even months, but at some point, usually when the temperature rises, you are likely to find the TV on the floor and a bent or snapped PLA TV bracket.

» **Acrylonitrile butadiene styrene (ABS):** This material is another common choice for functional parts, but it's tricky to print with because you need a heated build platform capable of running at least 110 ° C, as well as a hot-end configured for ABS. Usually, you need to disable the part-cooling fan to help limit warping in the ABS plastic as it builds layer on layer.

The example bracket is small, so it's suitable for ABS printing, I could have selected ABS for printing this part. Sometimes, the layer bonding strength of ABS isn't as good as that of PLA, so the better choice was polycarbonate.

» **The co-polyesters PETG, PTT, and PET:** These are ideal for this functional spool bracket. Their glass transition temperature is around 85 ° C, which is slightly lower than that of ABS and a higher temperature than that of PLA. Polyester materials are very good at layer bonding, which results in parts that are less likely to split at all the layer lines (*delaminate*, in other words) than ABS when they're used or put under stress. Finally, these plastics don't creep as badly as PLA and have a good level of impact resistance for general use and accidental abuse.



TIP

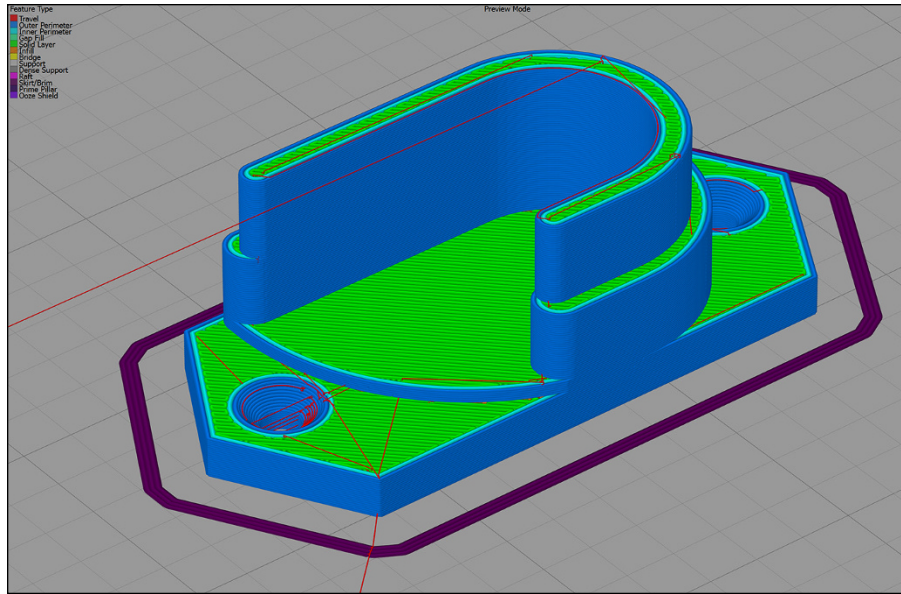
Another material that would be suitable is nylon (polyamide, which shares many of the properties I was looking for). The main downside to everyday printing with nylon is that it absorbs moisture from the air when just sitting around, so you need to dry most nylon materials before printing with them. (You have to do this every time you leave the spool out in the open for more than a few hours.) Nylon also resists many finishing techniques, resists many chemicals, and doesn't sand, file, or polish. Otherwise, nylon is a fantastic 3D-printing material. Not many other home 3D-printing materials can beat its strength and durability. Nylon just takes some experience and patience to use.

Orientation

Often, a 3D model has an orientation that's friendly to the 3D-printing process and allows material to be added layer on layer with minimal overhangs. But this natural orientation — often with a flat surface facing down and features sticking up vertically — isn't always the best for strength when the part is in use. When I designed this simple spool holder, I was thinking of exactly this problem, so the U-shape holder has more material and is wider at the base, resulting in more bonding strength between vertically oriented plastic layers.

Figure 16-11 shows the sliced Gcode layers of the spool mounting bracket in Simplify3D. You can use this visualization in most slicing programs to check that the tool-path is likely to print the model as expected and also to review the orientation of features on the model before printing. The model has been placed onto the print bed so the layered build process can print the model without the use of any support material or plastic overhangs. A weak part of the model is where the top of the flat section ends and the bracket starts to print on top of the flat printed layer. This upper printed section has only a small area to bond with the lower plastic layer, so the design uses a wider section to provide more bonding contact. This stops the weaker layer from becoming detached when the part is in use. After the first step is printed, we have gained strength in the vulnerable section, so we can reduce the wall thickness of the uppermost layers.

FIGURE 16-11:
Sliced Gcode
showing how
each layer bonds
to the one
before it.



If this part had been designed with a plate to screw to the wall and a thin U-shape protrusion to hold the wooden dowel, the U shape would likely snap off the base soon after entering use or after being knocked once too often.

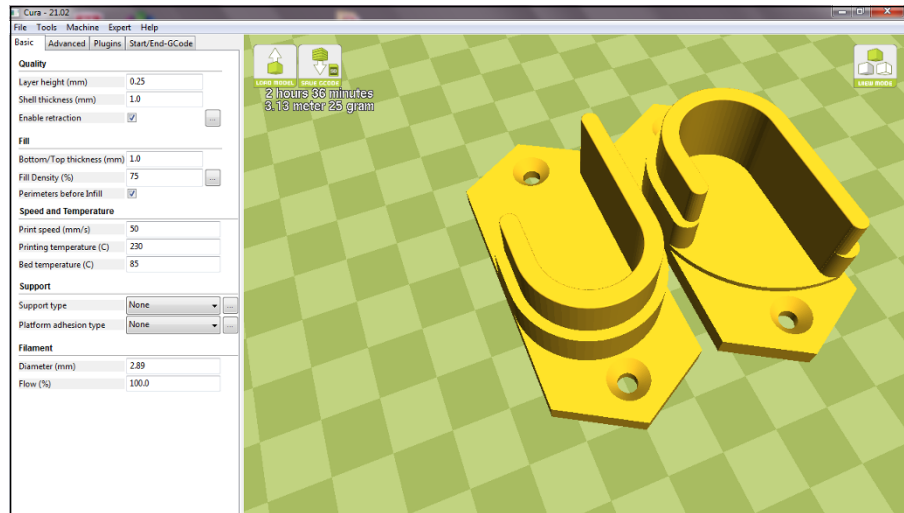
The part could have been designed to be printed in the 90-degree rotation, so the many printed layers would be aligned across the span of the U-shape holder. (See Figure 16-12 and imagine these parts had been printed at a 90-degree rotation to the build platform.) This alignment would make the part significantly stronger due to the fact that each layer of plastic projecting out from the bracket is now in-line with the wooden dowel, so the weight of the dowel and its contents does not put pressure onto single layers but a combination of layers at right-angles to the weight. But wait! Now the layers would also be aligned across the base rather than on top of one another. This means that, when you use a screw to secure the bracket to the wall, the screw will force the printed layers apart rather than compress them together. Forcing them apart will cause a split and weaken the bracket. As soon as any weight is added, that crack will cause the wall mount to fail. The original orientation compresses the many solid layers when the screw is inserted, which is preferable. This consideration is important, as you don't want the screw mount to be a point of failure when it's loaded with heavy spools.



REMEMBER

Most slicing programs allow a wide range of ways to print a 3D model, but getting the correct orientation on the build platform is often the most important aspect.

FIGURE 16-12:
The key settings
are shown here in
Cura.



Layer height

The height of each printed layer determines the appearance of the finished object and contributes some of the strength of the printed part. The relationship of the layer height range you can use with a certain nozzle size is directly related to the width of the printed line of plastic and the bonding strength (surface area) of each line on top of the previous layer. If you need functional parts to be strong but don't want to wait an extremely long time for them to print, a layer height that's 50 percent of the nozzle size is both strong and quick to print. The printer I used for my brackets had a 0.5mm nozzle fitted, so a 0.25mm layer height was selected. (The parts didn't need a super-high-quality finish; they just needed to be strong and solid.)

Nozzle size and perimeter outlines

The nozzle size you fit into the 3D printer determines how many perimeter outlines you need to meet the target for wall thickness. Model slicing programs approach the thickness of the outer perimeter wall in two ways:

- » **Cura:** With Cura, you decide on a wall thickness, which is usually a multiple of the nozzle size. For the example part, you'd select 0.5mm for a single perimeter or 1.0mm for two perimeters.
- » **Slic3r and Simplify3D:** In these programs, you select how many perimeter outlines you want to print for the object. (If you choose more outlines than can fit in the allowable space, the slicer creates as many as it can to fill the space.)



TIP

Perimeter outlines add strength to a model because they're always printed together, which creates a solid outer and inner wall of plastic regardless of whether the infill level inside the printed part is important for strength. For some parts, a thick perimeter and low level of infill is stronger than a single perimeter and a higher level of infill.

Infill level

Most newcomers to 3D printing expect finished objects to be solid, and they're often quite surprised to find that objects are almost always filled with mostly air (typically, 25 percent — or less — of plastic in a zigzag, honeycomb, or regular pattern of lines). Even with a single 0.5mm perimeter and a 25 percent infill level, a 3D-printed part can be very strong. Decorative models often use an infill level of 5 percent or are printed as hollow, with 0 percent infill material.

3D-printed parts used for building RepRap 3D printers are often printed with approximately 30 percent of infill. Some parts for high-torque gears and motor mounts require 50 percent to 60 percent infill. You rarely need to 3D-print a 100 percent (solid) infilled object, which is great because infilled objects use a lot of material and can take a long time to print.



TIP

If you ever try to go for a solid model, I strongly recommend still using a 95 percent or lower level of infill. If your 3D printer is not perfectly calibrated for material flow even +1 percent extra of excess plastic being deposited will eventually cause over-extrusion and either skipped or out of alignment layers, nozzle jams, or just a failed print.

For the spool mount example (see Figure 16-13), I selected a 75 percent infill level. The part is quite small and it needs to be strong, with more material-to-material contact on each layer. For a functional mount or bracket on a larger scale, you might print with around 50 percent infill; almost everything else would be 25 percent or less.

Environmental conditions for successful 3D printing

There are some environmental conditions that can either hamper or assist with the desktop 3D-printing process. New users of 3D printers may not realize that some of the extreme temperature, humidity, and ventilation changes that come with the change of seasons could pose a problem for 3D printers. I'm here to tell you that it can indeed be quite a big problem.

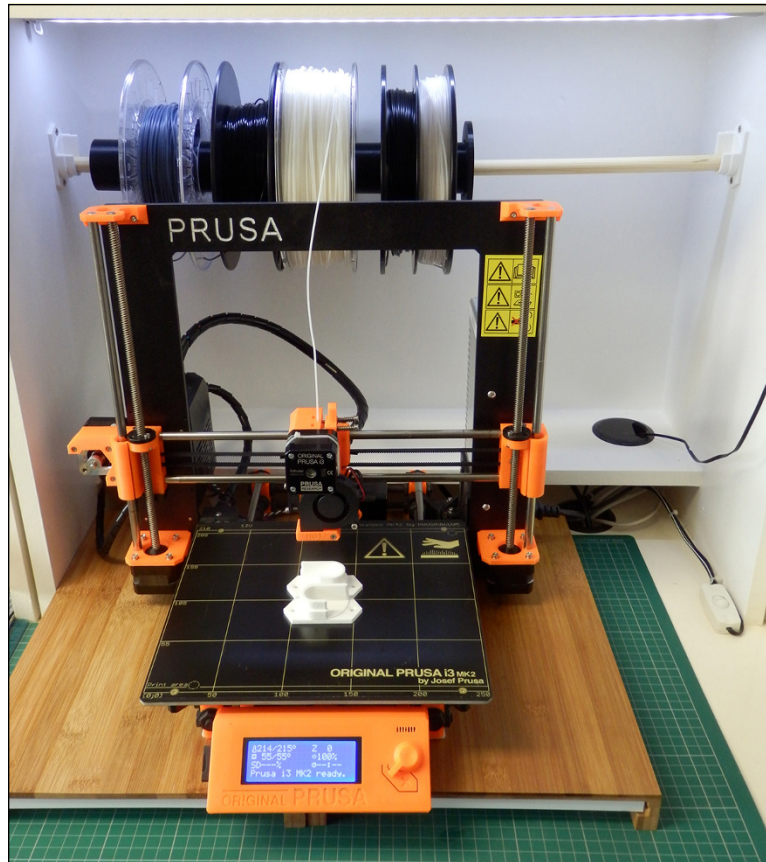


FIGURE 16-13: The finished mounting brackets, wooden dowel, and filament spools fitted and still in use six years later with the same printed parts.

First top tip — never try to 3D-print in ambient temperatures lower than 15° C (59° F). It's often just a recipe for disaster; you'll have poor bonding of the first layer, warping, delamination, failed prints, and just overall poor-quality results. If you print in a garage, outbuilding or anywhere where the temperature swings from zero to very hot, do consider moving to a more stable thermal environment. An ambient temperature that is too hot is also going to cause you problems. Fans can't cool molten plastic if they are blowing around very hot air, extruded material will sag more and give poor results in any spanning sections, and overall print quality will suffer. Sorry to be boring, but a stable office temperature of around 25° C (77° F) is ideal for most 3D printers and extruded materials.

Moving air is our next problem. If you have a 3D printer next to a window, door, or anywhere where air is likely to cause a draft across your 3D printer, try to eliminate any fast-moving air. A gentle breeze and air extraction or ventilation is a good thing — you certainly don't want to work in a sealed room. So, you do need some circulation all the time, but sudden gusts from a door or window are not good news.

The next enemy of successful 3D printing is moisture and humidity. Moisture in 3D printing filament is going to happen. For PLA, it's not usually a problem in most places around the world. For nylon, it's a problem wherever you are. All filament materials will take up moisture, and that can cause pops and crackles at the 3D print nozzle, bubbles in the extruded layers, and poor-quality layer bonding. If you find that your material looks fuzzy when printed or exhibits any pops (or even steam) when heated in the nozzle, it's time to dry it out. For nylon, this needs to be done every single time you print, even if you have put the nylon filament in a sealed bag. It'll just absorb moisture from the environment in the hours during printing and will need another drying process. Check with the material supplier, but don't be surprised if you need to dry out material before you use it. If you are in high humidity environment, it's only going to be more of a problem.



REMEMBER

Moisture will cause you problems. Depending on where you are in the world and what types of materials you are trying to print, it's worth exploring drying solutions and storage methods. A few companies have developed 3D print dry boxes, both for material storage and also for use during the 3D-printing process. These are still fairly new in the market; some don't perform particularly well; and others are considerably more expensive for what is essentially a glorified sealed box. Alternative methods such as a dehydrator for fruit and vegetables, often in a round stack configuration, can be bought at a low cost and can help reduce moisture in spools of filament.

Desiccant gel packs, sealed zip lock bags and airtight storage boxes are all good tools to battle moisture getting into your filament spools.



TIP

I designed a DIY filament dry-box for using materials while printing. It's easy to make for a low cost of standard off-the-shelf components and a few 3D-printed parts. You can find the design at <https://richrap.blogspot.com/2018/02/diy-heated-drybox-for-3d-printing.html>.

Postprocessing, Recycling, and Finishing an Object

After completing a 3D print, you have some further options to add strength and a fine or smooth finish. In this section, I discuss some postprocessing and finishing options, along with exciting materials that are now available for desktop 3D printers.

Manual finishing

Sanding, filing, cutting, and polishing are ways to manually refine many 3D-printed plastic materials. You can use polishing wheels and sanding machines, but be sure to run them slowly; otherwise, they tend to melt the plastic rather than smooth or polish it.

Some materials, especially composite metal-filled filaments, can produce a wonderful finish with a little effort and patience. Figure 16-14 shows a 3D-printed object being polished. The stainless-steel, metal-filled filament begins to shine with the application of some manual rubbing and buffing. (You can get the model from Thingiverse at www.thingiverse.com/thing:29114.)

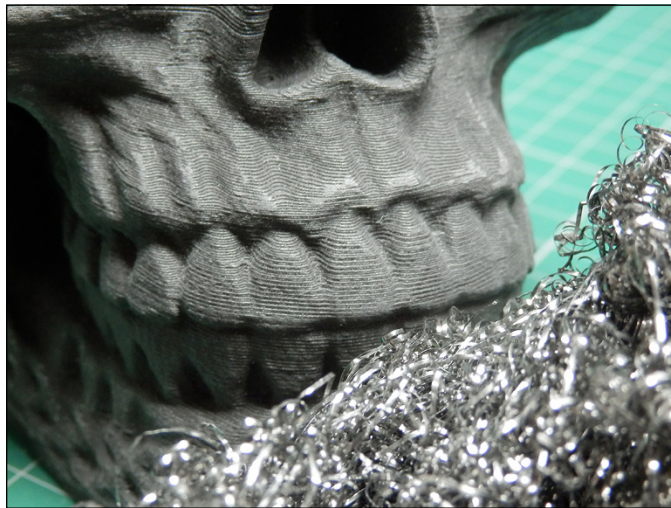


FIGURE 16-14:
A 3D-print object
being polished.

*Celtic Skull model designed by artec3d and printed in Proto-Pasta
Stainless steel 3D Printing filament.*

Rusting 3D prints

It may sound odd to say that a 3D-printed object can rust, especially when we know these are thermoplastic, but if you decide to 3D-print an object in a filament material like ProtoPasta magnetic iron, you can post-process it to a wonderful rusted finish just by using a little salt and vinegar spray. (See Figure 16-15.)

FIGURE 16-15:
3D print of a terracotta warrior in ProtoPasta magnetic iron being rusted.



Lolitakuma / <http://www.thingiverse.com/thing:1028560> / last accessed 10 August, 2023 / CC BY-SA 3.0

Filling, smoothing, and painting

You're occasionally going to need to hide those 3D-printed layer lines with a filler or a nice smooth painted finish. For one model I wanted to print at full size, this process involved printing multiple sections, bonding the sections together with super-glue, filling and sanding the join lines and the printed layer lines, and then applying multiple layers of spray filler paint, and finally adding a few coats of zinc car spray paint. (See Figures 16-16 and 16-17.) With a little more work, I could have polished my model to a shine. (If you don't like the sound of all that sanding, filling, painting, and polishing, then take a look at the assisted finishing process in the next section.)

Assisted finishing

When an automated or assisted finishing process is desired (for example, the use of a machine to lower a printed part into vapor or solvent baths to make the plastic shine), specific plastic formulations are being created and devices are being developed to help with the postprocessing of 3D-printed objects.

The Polysher, shown in Figure 16-18, uses polyvinyl butyral (PVB) plastic 3D-printing filament to print parts on your desktop 3D printer as you normally would. You then place the printed parts into the Polysher machine along with a small amount of isopropyl alcohol (IPA). The Polysher vaporizes the IPA solvent, which slightly melts the outer surface of the PVB-printed object to smooth out all the fine lines you always see on any 3D-printed object. The Polysher seals in the vapor and controls the generation and duration of smoothing to produce a shiny finish, as shown in Figure 16-19. This process can also make the final object

watertight and strengthens the printed model due to the fact the layers have been remelted together. The result is a model that looks like it was injection molded rather than 3D-printed. This is basically what every product designer would need in order to complete the finishing of a 3D-printed model without having to invest lots of hard work.



FIGURE 16-16:
Part of the
Nefertiti bust
printed and being
sanded ready for
painting.



FIGURE 16-17:
Assembled
Nefertiti bust,
painted in zinc
and ready for a
final polish.

Richard Horne / <https://www.youmagine.com/designs/nefertiti-in-sections-up-for-3d-printing-full-sized> / last accessed 10 August, 2013



FIGURE 16-18:
The Polysher.

Image courtesy of Polymaker

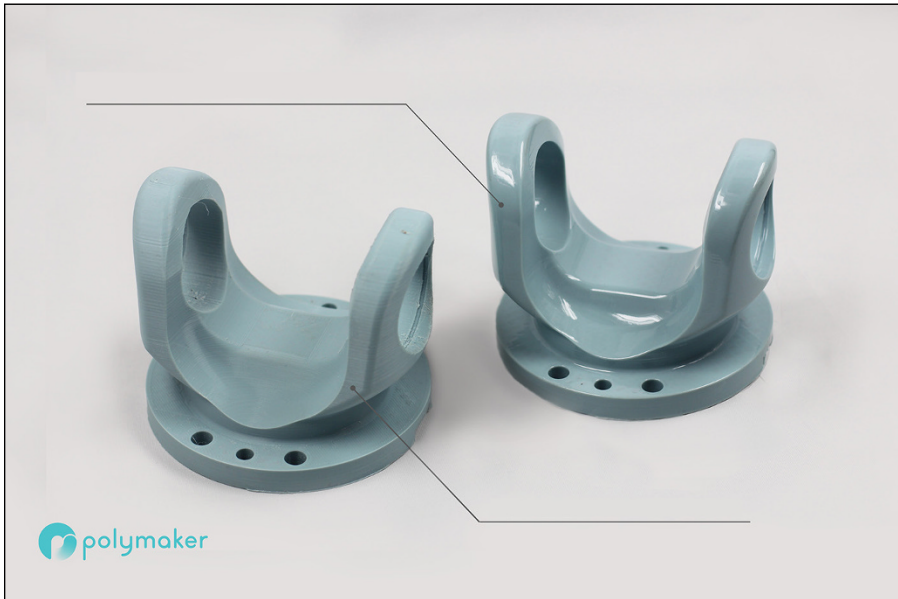


FIGURE 16-19:
Before (left) and
after (right)
the use of
polysmooth
material and the
Polysher.

Image courtesy of Polymaker



WARNING

Alternative methods of finishing an object can be complex and difficult to manage, so consider carefully whether you want to attempt using them. Using acetone on ABS printed objects, for example, melts the surface and makes it smooth, fuses the layers, and adds strength. The result is a finished, glossy appearance for the 3D-printed object but . . . you need to take great care with acetone and do your research. One thing you'll discover is that acetone and isopropyl alcohol are both flammable. Acetone smoothing of plastic is widely described on the Internet, but I don't recommend using this finishing process. Unless a professional device similar to the Polysher becomes available for ABS or other materials, avoid acetone smoothing of ABS.

Coatings

Dipping or painting on liquid resins or coatings like the XTC-3D from Smooth-On is a straightforward way to finish a 3D-printed part. This method often adds strength and provides a smooth finish.

One negative aspect of applying coatings is that coatings can change the size of the finished object. They also sometimes hide or fill small details of the model that you may want to remain visible.



WARNING

Read all manufacturer's instructions and wear appropriate protection before applying a coating to your object.

Printing Big: Bonding and Joining Parts

Occasionally, you may want to print 3D objects or models that are bigger than your 3D printer's build area.

If the model isn't made of smaller parts, you can print oversize objects by cutting the model into sections sized for your 3D printer.

This process is much easier than you may think. You can use several free or open-source applications to split a model into smaller sections. Figure 16-20 shows the use of Netfabb to cut a scaled-up dragon model into smaller parts so that it can be printed on a standard Prusa i3 MK2 3D printer. (See the nearby sidebar "Adalinda: The Singing Serpent.") The model is first scaled up by 600 percent so that the final assembled model will stand 883mm tall rather than 147mm. (See Figure 16-21.)

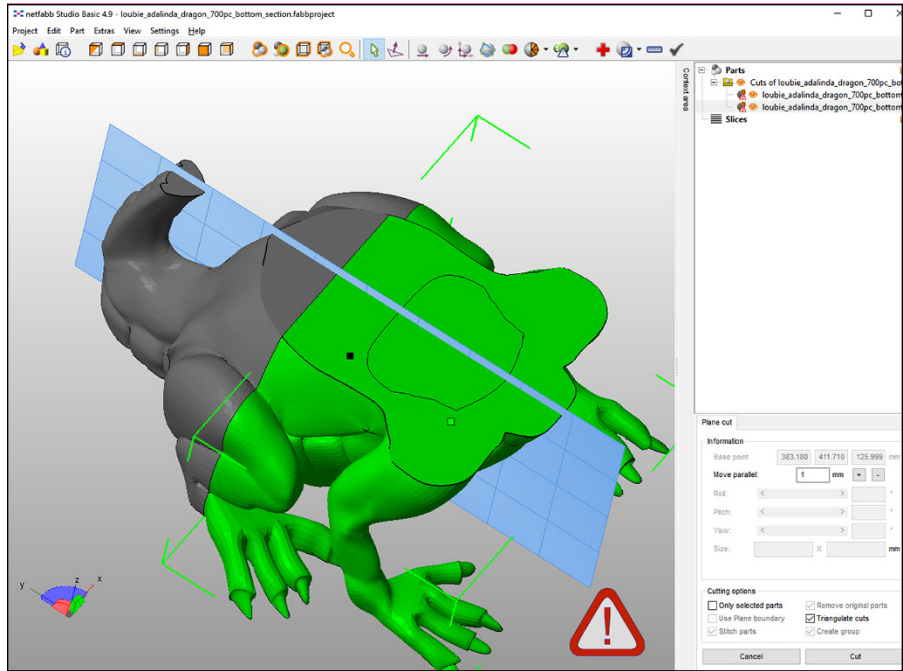


FIGURE 16-20: A large model in the process of being cut into sections.

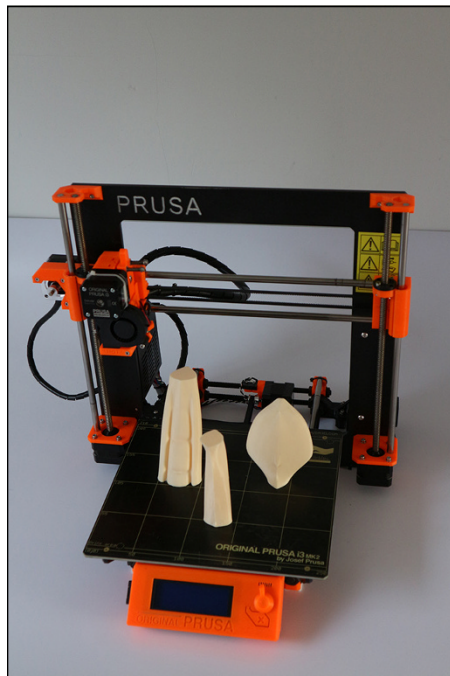


FIGURE 16-21: Sections of the tail scaled up 600 percent, cut into sections, and then printed as a plate of parts to be glued back together after 3D printing.



TIP

When using an application like Netfabb, you can load in an STL model and alter the scale of the model by clicking on Part-Scale. After scaling up any model, you can then select a cutting point in the X, Y, and Z planes. Perform the cut and as you see the warning triangle in the bottom right of the screen (refer to Figure 16-21); remember to repair each section using the + Icon repair tool before saving each part as a separate STL file.



REMEMBER

The sections of any model you cut up still need to be printable, so you may need to rotate sections both before and after cutting in the X, Y, or Z planes. Whatever flat sections you end up with need to be rotated flat to the build platform. Netfabb has an easy Align-to-Bottom-Plane tool for automatically rotating a model to a selected surface.

Figure 16-22 shows the almost-complete model. The various sections were printed in PLA and glued together; any seams or defects are smoothed out with flexible acrylic filler. After the parts are assembled, the object can be sanded and painted as required.



FIGURE 16-22:
The almost-complete model.

ADALINDA: THE SINGING SERPENT

Adalinda: The Singing Serpent was designed by Louise Driggers and is licensed under Creative Commons. The normal size of this model is 147mm high. You can get the original model at www.thingiverse.com/thing:246198.

By cutting a design into components, you can print very large-scale models that can be both strong and light because the honeycomb nature of 3D-printed models allows for minimal use of material.



REMEMBER

You can use many paints and fillers to assemble the parts, but some glues don't stick to certain types of plastic. Make sure to perform a test before trying to assemble a large model. Friction welding or ultrasonic bonding of plastics can help when two parts need to be joined.

Certain materials also limit how large your components can be. ABS warps significantly more as the printed object gets bigger, for example.

Adopting Green 3D Printing

One of the most common assumptions people make about 3D printing is that you can recycle and reuse plastic over and over again. Unfortunately, it's just not so. When you get a failed print, you have no simple way to get that material back into a filament strand that you could use again. Some companies, however, are looking at ways to reuse failed prints and other types of plastic waste, from beverage bottles to doors that may otherwise end up in landfills or the oceans.

Refil, a Dutch company, supplies recycled ABS made from car dashboards and polyethylene terephthalate (PET) from plastic bottles. The company is also investigating the use of recycled high-impact polystyrene (HIPS) generated by waste plastic from domestic appliances such as refrigerators. As you might expect, this recycled 3D-printing filament is supplied on eco-friendly recycled cardboard spools.

The most common way to transport coiled 3D-printing filament is unfortunately on a plastic spool, which can be around 20 percent of the total shipping weight and is usually discarded after use. Filaments also come in all shapes and sizes that

you somehow need to fit on your 3D printer. A few common standards are starting to emerge for the size and shape of a spool of 3D-printing filament. If you are lucky, the most common spool types usually have 750g or 1Kg of material and a 50mm hole in the center. Some 3D printers now have added mounting methods for a typical spool, but just as many leave it up to the user to decide what to do with several hundred meters of tightly spooled filament coils (that will tangle and jam halfway into a multi-hour print if they're not carefully managed).



TIP

This chapter includes a guide to designing a filament spool holder bracket to help with the tangling problem. It's often the first problem new users are faced with, and if you don't have a good method for mounting and allowing the spool to freely feed, you will get countless extruder feed failures or poor-quality results.

Examining home filament extrusion

Extruding your own 3D printing filament is a common thought for new users. You would think that it is relatively easy to accomplish, but it's actually quite difficult to achieve. I could write an entire chapter about the trials and tribulations of separating mixed waste plastic into different types, shredding it into a ground-up material, adding virgin pellets, drying and sorting, and then extruding this mix into a spool of filament. I have done this a number of times using home-made equipment and even a borrowed \$10,000 desktop extruder. It's all really difficult and regardless of the good intentions to save you money or generate less waste, it's usually not at all the outcome.

The basic problem is that industrial filament extruders use a lot of high-tech equipment to keep everything moving along at the exact speed and at stable extrusion temperatures resulting in the perfect filament produced with better than 0.1mm tolerance and a round profile.



REMEMBER

Even though most professionally produced recycled filament is just a blend of some recycled plastic mixed with virgin pellets and extruded on (very expensive) manufacturing lines, if you were to try to replicate this at home by scaling everything down, it would soon become a very labor- and time-intensive process with a lot of trial and error, resulting in a lot of waste and expended energy.

I don't want to put you off recycling or further investigating these desktop extrusion systems, but the reality is a little like having your own small wind turbine at home. It sounds like a good idea, but it's not always going to be reliable (count on it breaking down at some point) and the energy output is unlikely to ever pay for

the initial purchase price, installation, and ongoing servicing. On the other hand, a large-scale wind-farm can be absolutely perfect if you want to deliver low-cost energy to thousands of houses.

Maybe in the future we may be able to print directly from pellets or ground recycled plastic. That (far off?) future would be great, but the situation at the moment is that even dedicated desktop extrusion systems are often not economical or viable to run even for a makerspace, school, university, or business. Unless you really need to experiment with plastic blends or plan to start up a professional extrusion business some day, I can't recommend investing a lot of time or money into this. It's simply more sensible and sustainable to buy ready-made filament at this time.

Aiming for sustainability

Some manufacturers are now finally starting to use cardboard or recycled filament spools. Cardboard spools are a great innovation, one that is helping to eliminate single-use plastic waste from the 3D printing consumables market. Please do consider supporting manufacturers who produce filament on sustainable spools on a cardboard or a reusable spool system. If every user refuses to buy materials supplied on a single-use plastic spool, we will all be one step closer to eliminating more wasted plastic that will end up in landfill.



REMEMBER

Not all manufacturers are switching away from plastic spools, which can weigh 200g or even 300g. You, the consumer, are paying for the extra weight to be delivered, and then you have to try to recycle all that plastic — often not an option with many generic “black plastic” unmarked spools without a recycling mark, so they automatically end up in landfill because no one can identify what black plastic material it's made from. Cardboard spool cores, however, can easily be recycled.



TIP

Some low-quality/low-cost filament suppliers have been known to hide all their scrap or waste plastic in spools of black filament. If you run into problems using a spool of black material, it may have a mix of materials or be of much lower quality than you may have expected. If that happens, consider moving to another supplier. Some suppliers are now also being up front about this waste recycling and market these black spools specifically for experimentation or draft printing; they can be useful if you are trying to refine a printed model before using a much more expensive material for the finished print. We are seeing more and more recycled filament, and that's not a bad thing. Just be extra careful with black as it's an easy color to hide fillers or waste.

INTRODUCING MASTERSPOOL

Some manufacturers are working now to come up with alternative spool systems. For many years I have encouraged filament manufacturers to move away from a single-use spool and onto a more sustainable solution. The excuse for not doing so was often that their production machinery could not handle cardboard spools in the automatic manufacturing process. The reality was also that a single-use plastic spool was often only approximately \$1, and a cardboard alternative would be slightly more expensive. I listened, made lots of notes and worked with a few companies to explore expanded foam spools that could be reused. Again, costs and tooling or machinery made a few of these ideas difficult to bring to production.

It's also just not viable to send back empty spools to the manufacturer; the cost is too high; and that's also just adding more transport and carbon footprints. That's when I decided to discuss an idea with the 3D-printing community about a two-part reusable spool that could be 3D-printed. This was my Masterspool concept that I published on my 3D printing blog at <https://richrap.blogspot.com/2018/01/masterspool-proposed-standard-for-3d.html>

The idea of Masterspool is for manufacturers to supply a wrapped raw filament coil which could be slipped onto the 3D-printed Masterspool and used on normal spool holders for 3D printing. This tough, reusable spool could be printed or mass produced as long as it's being reused multiple times so more manufacturers can continue to ship just the coils out to customers using the Masterspool system.

It's taken time to be picked up by the manufacturers, but slowly we are now seeing more of these types of reusable spool systems. Masterspool is an open standard, so I always try to encourage compatibility because compatibility is good for suppliers as well as users.

I encourage you to try it out, or at least use materials supplied on a cardboard spool or any type of reusable spool system. If your filament supplier is still using single-use plastic, even if it's recycled, please consider asking them if they intend to switch over to a more sustainable product.

Using a Web-Based 3D-Printing Interface

As the electronics used in desktop 3D printers become more powerful, more web-based user interfaces are cropping up. These interfaces often allow a 3D printer to be connected, set up, and controlled via a wireless network. In this section, I'll have you look at two of the most popular web-based 3D-printing user interfaces.

OctoPrint

If you need to remotely control and monitor your 3D printer or want to network it, take a look at OctoPrint (<http://octoprint.org>). Designed, maintained, and programmed by Gina Häußge, this open-source Raspberry Pi-based application allows interfacing with almost any 3D printer that has a USB connection. You can use a webcam or your computer's camera to monitor the live 3D-print process. You can send new files to your 3D printer and start or stop print jobs via network or wireless access through the Raspberry Pi computer.



REMEMBER

The remote monitoring I describe here doesn't mean you can ignore warnings about not leaving your 3D printers unattended. This sort of remote monitoring and remote access is meant to help you keep a check on machines that may be in a different room while you or someone else is keeping an eye on them at regular intervals.

Duet

The Duet web control (<https://www.duet3d.com>) runs directly on the 3D printer's electronic platform and doesn't require a separate controller (such as a Raspberry Pi). Your 3D printer must use a Duet electronics set or another ARM-based electronics platform that the RepRap firmware can be ported to. The Duet Web Control panel allows remote setup, transfer, and control of printing jobs.

6

The Part of Tens

IN THIS PART . . .

Check out ten examples of additive manufacturing and personalization.

Take a look at ten 3D-printed designs that would be impossible to fabricate using traditional manufacturing techniques.

Take ideas from these concepts to use in your own 3D-printing projects!

Chapter **17**

Ten Examples of Direct Digital Manufacturing and Personalization

Additive manufacturing isn't a futuristic technology; it's already in place and in use across many industries. Created for rapid prototyping, additive manufacturing has steadily migrated into direct digital fabrication of consumer products. As material options expand and the complexity of 3D-printed objects increases to include integrated mechanical components and electronics and enhanced structural designs, a broader spectrum of products can be manufactured directly from electronic files and raw source materials. This chapter discusses ten examples of this type of direct digital manufacturing.

Producing 3D-Printed Food

Cornell University and other research sites are exploring 3D-printed foods such as vegetable wafers and meat pastes. Under a NASA grant, a small company in Austin, Texas, is working on a 3D printer that will use materials from long-shelf-life powders, suspended oils, and water to create pizzas that will cook to completion on the heated build plate of the printer. Future astronauts will depend on such systems to prepare food during long-term travel to Mars and beyond. Other

researchers are demonstrating the use of lab-grown meat cells to create 3D-printable hamburgers and steaks that don't require raising and feeding animals. These developments will start to provide alternative options for food production and could significantly improve animal welfare and overall food quality. Also, this technology may one day provide travelers and explorers practical, portable supplies and allow sufficient protein consumption even in the absence of farms. Cornell's students already print custom cakes and finger foods using a growing range of ingredients that have been prepared for a paste extrusion process.

Printing Tissues and Organs

Beyond the simple biological materials needed to print muscle tissues and foodstuffs, additive manufacturing bioprinters are being developed to create complex multicellular matrices that can grow into functional organs and replacement tissues for human recipients. One benefit of these designs is that they can use a recipient's own cells, producing implantable replacements that don't require a lifetime regimen of immunosuppressive medications to prevent transplant rejection.

One example of this type of printing is 3D-printed fine sugar strands in a complex multidimensional array suspended in culture gels. After printing, the sugar is dissolved; then fluids similar to blood are circulated inside the structure to allow for growth and nourishment of the cells. For example, these cells may be a framework into which bladder cells can grow. Currently, complex critical organs such as multicellular livers are being tested. Also, small 3D-printed samples of different types of organs are being used to test new pharmaceuticals and medical treatment protocols outside living bodies.

Fashioning Biological Replicas

Until bioprinters can create replacement living tissues, 3D printing has a promising medical role, because it allows the fabrication of prostheses and implants perfectly matched to the original body part (or mirrored from functional body parts). Gone are the days of crude wooden peg legs and articulated hooks for missing limbs. A prosthesis can be transformed through 3D printing into not only a functional replacement, but also a work of art that accurately reflects the wearer's personality.

Companies such as Open Bionics are making great progress in low-cost replacement limbs. The Ada bionic hand, as shown in Figure 17-1, is a fully functional

open-source robotic hand. The Ada hand uses low-cost electronics and actuators along with plastic components that can be produced on a desktop 3D printer. Anyone can print and assemble this bionic hand and then control it via a USB link to a computer.

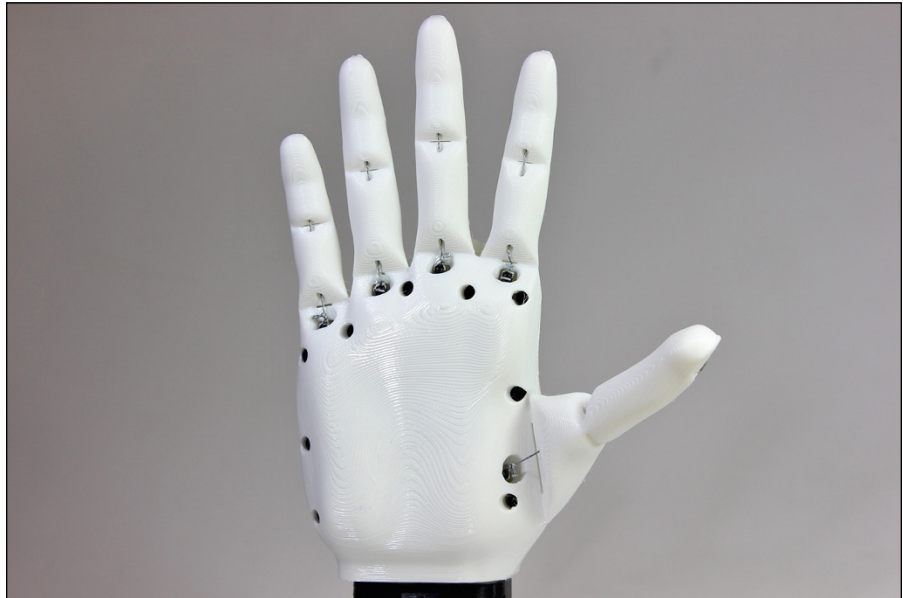


FIGURE 17-1:
The Ada bionic
hand from Open
Bionics.

Image courtesy of Open Bionics

The company's original products were 3D-printed but used mechanical action to activate the closure of fingers to grip an object. In recent years, Open Bionics has developed electronically activated, user-controlled hands like Ada. This technology isn't new, but 3D printing ensures a perfect fit for every user at a lower cost and faster production speed than existing casting methods can provide — especially important for children, whose prosthetic devices need to be changed regularly during growth.

Crafting Clothing and Footwear

3D printing allows the creation of textiles and other clothing. One such product is custom-fit athletic wear that provides better traction and reduced weight. Another product is clothing uniquely tailored to each wearer's measurements. Even if two people wore the same dress to a ball, the dress would appear to be two different creations suited to each wearer.

Researchers are also developing ways to spray material fibers in three dimensions directly on a 3D-printed pattern form. This process, combined with subsequent steps to soften the material, can produce an item like a T-shirt without any stitching or assembly required.

Customizing Jewelry

Among the earliest small 3D-printed items were customized plastic earrings and pendants. Today, industrial 3D-printing processes can produce solid forms in various metals, including titanium, brass, and bronze. The most difficult metal to 3D-print is gold because it reflects 90 percent of the laser beam's energy, making sintering of the gold powder extremely challenging. Gold 3D printing is available from select suppliers, but it also costs several hundred thousand dollars to fill a machine with enough gold powder to make the process economically viable. Individual designers can now use many online 3D-printing service providers to 3D-print custom jewelry in many different materials. As desktop 3D printers produce smaller and more detailed objects, producing and customizing intricate artworks will be even more accessible to individual designers.

Making Hollywood Spectacular

Model makers have long created sets and props for movie productions. 3D printing makes it possible to custom-fit a costume to an actor. It's now common practice to use 3D printing in almost every aspect of film and TV production. For the stop-motion film *The Pirates! Band of Misfits*, Aardman Studios 3D printed all interchangeable parts of the main characters, which amounted to more than 20,000 interchangeable heads to accommodate the many emotions and facial features used during production. Full-color models can be 3D-printed directly, but it's still more common to use 3D printing for rapid production of the model, while a team of painters finish each part by hand. Using 3D printing is really now the only way to reduce both time and costs for production companies that require custom costumes or thousands of slightly differing parts.

Creating Structures

3D printing can produce structures big enough to live in. This technology will enable astronauts to fashion habitats and satellites in space, using materials derived from asteroids and other sources rather than carrying materials from Earth at great cost.

Eventually, entire houses on Earth will be crafted in place. Right now, 3D-printed concrete modules are being used to repair denuded reefs and other damaged elements of the ecosystem. Researchers at the University of Washington and in Europe are testing systems aimed at scaling up printers so that they can craft entire buildings.

Reaching beyond the Sky

Designs for high-performance turbines and jet-engine compressor blades can be created as single-print objects rather than traditional assemblies of smaller components. 3D printing can bring a significant advantage in the reduction of component parts. 3D-printed components that are built with a layer-by-layer process can be more intricate or complex, especially with internal geometry that could not be made with a subtractive machining process. Having fewer parts to join in an assembly can reduce weakness and often the overall weight of the product. For an aircraft, that can mean a significant saving on fuel and running costs and can reduce the possibility of mechanical failure.

General Electric is taking advantage of this capability by updating designs during the production cycle simply by changing the files used to fabricate jet-engine components. NASA has successfully tested 3D-printed rocket nozzles and other high-pressure components needed to let aircraft and spacecraft slip “the surly bonds of earth” (as John Gillespie Magee, Jr., wrote in his poem “High Flight”). As private industry begins to join with governments in the exploration of space, we will see the use of additive manufacturing play a significant role in cost reduction and design iteration.

Constructing Robots

Automation and robotics are transforming the world into a highly interactive, self-controlling environment. Factories once filled with hundreds of workers exposed to hazardous environments are now automated and managed from positions of relative safety by remote operators. The tools used for these purposes are often custom-built designs, but 3D printers enable small runs of custom robotics suited to a purpose too narrow to draw the attention of large industries. Complex linkages and connections can be easily created on 3D printers to form one-off brackets and other elements to fit the need at hand. Innovations can be added and tested easily to enhance the capability of robots.

As artificial intelligence continues to grow, personal mobile robots may perform many physical tasks. The open-source community is creating almost life-size humanoid robots, developed in the open-source community, using 3D printers to produce the main structural and motion elements. Advanced microelectronics and battery capacity still have a long way to go, however, before fully bipedal robots operate for more than a few hours at a time.

Printing 3D Printers

3D printers make it possible to fashion more 3D printers by using basic robotic controls and linkages together with custom brackets and common off-the-shelf hardware. When fundamental patents on fused deposition modeling (FDM)/fused filament fabrication (FFF) thermoplastic extrusion expired in 2006, Dr. Adrian Bowyer's Self-Replicating Rapid Prototyper (RepRap) project was released as an open-source design, and a capability once open only in labs and high-end manufacturing facilities became available in a household appliance that cost less than the first LaserJet printers. Thousands of RepRaps and their offspring are available today in makerspaces, schools, libraries and office-supply stores. Each printer can print many of the components for another printer in turn, using open-source designs that are freely available online.

More possibilities await as additional fundamental patent controls expire in the coming decades. The original stereolithographic (SLA) technology, for example, has fallen out of patent protection and is being used in systems such as the Form 2. Selective laser sintering (SLS) patents expired in 2014, opening commercial and hobbyist opportunities by making personal fabrication possible for plastics, metals, ceramics, and other granular-powder materials. Companies such as Sharebot in Italy are making SLS systems for a fraction of the cost of the systems used just ten years ago.



REMEMBER

Metal sintering has requirements that are slowing its wider adoption, such as environmental controls, specialized gasses, and high-powered lasers that require special enclosures to protect their users. Granted, metal sintering is more complex, elaborate, and costly than FDM/FFF thermoplastic printers and resin-based SLA printer.

Chapter **18**

Ten Impossible Designs Created Using Additive Manufacturing

Some designs would be impossible to produce via traditional manufacturing processes. In some cases, they'd be too expensive or difficult to manufacture. In other cases, the necessary technology doesn't exist. Due to the unique layered process of additive manufacturing, many of these "impossible" designs have become reality. This chapter discusses ten unique products that are best produced with an additive manufacturing process.

Personalized Objects

At some pop-up events around the world, 3D printers are being used to personalize a cocktail drink order by being able to print on demand a simple cocktail stirrer in bio-plastic with the person's initials. Derived from contactless drink payment, a simple model is automatically generated and processed, sent to a 3D printer, and printed in minutes while the cocktail is being elaborately made by the bar staff. It would be impractical to have every combination of a person's initials made and in-stock via traditional methods of plastic injection molding. Using 3D printers to produce an object like this at the point of sale is still a waste of plastic and has questionable value as an ongoing enterprise, but as a marketing stunt and a way to promote your event, bar, or club, it could be quite effective.

More elaborate custom 3D-printed objects can often now be ordered online for delivery in a specific color, with added customer-specific requirements such as the spider web guitar shown in Figure 18-1. Details such as serial numbers or a maker's signature can be included in the printed design so that each printed object is created with its own identity.



FIGURE 18-1:
This guitar has
been customized
with a spider-
and-web motif.

Image courtesy of Olaf Diegel

Medical Implants

Unlike traditional implants, which use standard rods and other adjustable components, 3D-printed implants can be designed to perfectly complement the recipient's body. Another advantage is that such objects can be printed with complex inner patterns. Trabecular lattice structures allow bone tissue to grow directly into the implant itself through a process called osseointegration. The resulting cranial cap or joint replacement incorporates the patient's natural tissues and can become part of the patient's body without being attached by screws or other mechanical fasteners, which can wear away and cause further damage to bones over long-term use.

In other applications, 3D-printed titanium is used for replacement bones and implants. One significant benefit of 3D-printed titanium is its slightly porous structure, with which the body can more readily accept tissue growth faster than it could with a solid-machined titanium part.

Dental Repair

Metal 3D Printing from Renishaw is doing for 3D-printed replacement teeth what other manufacturers did for 3D-printed hearing aids. Many years ago, hearing aids didn't fit very well. They were either painstakingly handmade from casts and molds for each patient or chosen from a selection of generic mass-produced sizes that may or may not fit. Today, around 95 percent of all hearing aids are 3D-printed. Now the dental market is undergoing a similar change. Using some of the world's most complex metal 3D printers, Renishaw's machines are at the forefront of mass-custom manufacturing for the dental market.

Using incredibly strong cobalt chrome metal powders as fine as powdered sugar, with ceramic coverings, every tooth, bridge, and crown can now be custom made for every client. 3D scanning determines the size and shape of the denture before adding a serial number used for tracking in the manufacturing process. Plates of these teeth are grown and post-processed for multiple patients. (See Figure 18-2.)

FIGURE 18-2:
A closeup of a dental build plate using Renishaw metal additive manufacturing machines.

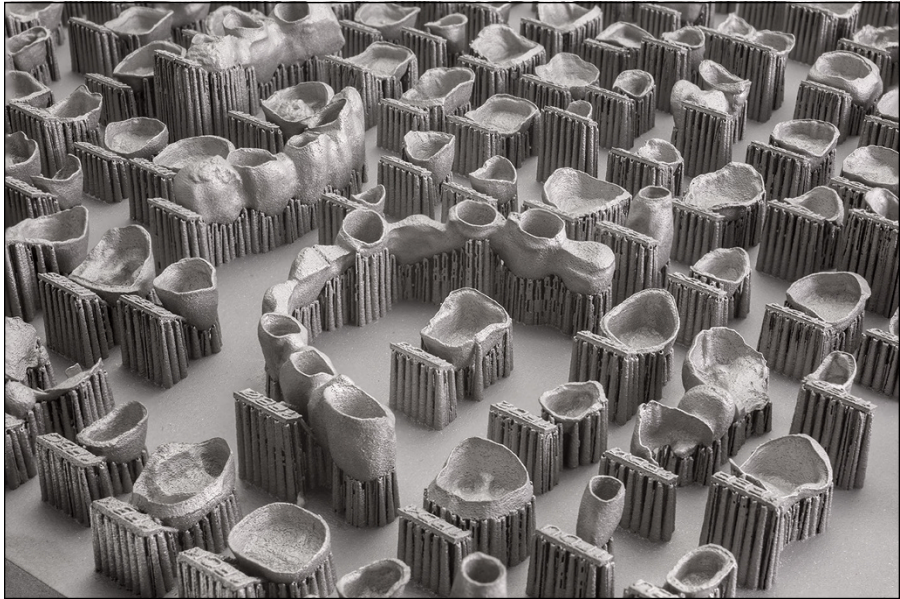


Image courtesy of Renishaw

Self-Deploying Robots

Micro robotic insects (microbots) can be created to fashion integrated components capable of transforming into useful configurations directly out of the 3D printer. Traditional equivalents require subassembly steps before they can be deployed, but the 3D-printed versions can be deployed in a single automated fabrication facility. These small robots are being used to search disaster zones for signs of life. When a robot detects noise or thermal energy, multiple robots work together to triangulate the coordinates to the outside rescue teams.

Printed Drones and Aircraft Parts

3D-printed parts for drones allow almost unlimited customization to accommodate changes in flight and weather conditions and other unpredictable requirements. Doing this fabrication and customization where needed or required (rather than in a factory before the aircraft is shipped out) means that the correct sensing equipment or style of design to suit terrain or weather conditions can be selected for the current situation.

These drones are lighter in weight than their traditionally manufactured equivalents because their strength depends on cleverly designed internal structures rather than a solid block of material. This reduction in weight allows more drones

to be fabricated from the same pool of raw materials. Also, each drone can operate for a greater length of time using the same amount of fuel.

Airbus and other manufacturers hope to apply these same efficiencies to full-size aircraft as legislation and approvals for 3D-printed materials allow more complex and safety-critical structural parts to be used. 3D-printed parts for aircraft manufacture are certified for use now. The widest use of 3D-printed parts in today's aircraft tends to be smaller plastic housings and custom fabricated parts that traditionally require costly tooling for a relatively small number of components — the use of many different shaped cable ducts to channel the mass of wires used by aircraft today, for example. Using 3D-printed cable ducts can reduce tooling costs and also increase design flexibility and reduce the cost of assembly wiring. 3D printing allows unprecedented design flexibility so tooling can be eliminated completely, lowering production cost and reducing time-to-market.

Meanwhile, hobbyists are using desktop 3D printers to produce custom drones from materials such as carbon fiber. These materials offer reduced weight and increased strength and enable the creation of designs vastly beyond off-the-shelf drones.

High Performance, Lightweight Engine Cooling

The high-performance Formula 1 motor sports teams around the world have fully embraced the capabilities of 3D-printed metal manufacturing, especially for highly complex shaped parts that would be impossible to machine or cast using any other method. Advanced lightweight engine cooling components allow these sports cars to achieve greater performance during a race season. The custom designs can also be monitored for performance and further developed, printed and tested to quickly optimize every aspect of the material surface area to assist with cooling. Many other parts of a Formula 1 car are also now 3D-printed to exactly match proportions and fit the driver of the vehicle.

Custom Objects Created in Space

Because additive manufacturing techniques such as fused deposition modeling (FDM)/ fused filament fabrication (FFF) don't rely on gravity for layer construction, they can operate upside-down or in microgravity environments such as the International Space Station. NASA has already sent 3D printers to space, and astronauts have used them to print tools and small replacement parts. This

technology will allow future astronauts to travel without having to carry spares of all the tools they may need in their explorations. Apart from the raw materials needed for the 3D-printed parts, it would be advantageous for multiple 3D printers to also produce spare parts for themselves, sustaining the ability to make whatever tools or devices required without the need for a trip back to Earth for repair.

Art on Demand

3D printing systems are being used to faithfully reproduce works of art with far more depth than a flat image or photographic print reproduction. 3D printing of multiple layers at fine resolutions can reproduce brush strokes, indents in paint, and even accurate degradation of damaged parts. This is a great way for museums to share works or allow a copy to be on general display while the real artwork is away or unavailable.

In recent times 3D printing and 3D scanning have been used to re-create sculptures and works of art from destroyed collections around the world. As more cultural history is at risk of damage from war or natural decay, many historians are using 3D scanning and high-resolution image captures to archive a digital copy that a 3D printer could reproduce if required.

Locally Fabricated Items

Markus Kayser's design for the Solar Sinter and current work at the NASA Jet Propulsion Laboratory — or at EU sites for space technologies — are demonstrating the fabrication of complete objects using nothing more than local solid materials and sunlight. Whether the printed objects are bowls formed of glass fused from sand or structures formed from rocks, these technologies represent some of the purest forms of green engineering: Final products could be ground up and returned to their natural state after use, with no further chemicals or fuels required.

Body Parts

One of the most amazing capabilities of 3D printing is making body parts such as organs with complex inner configurations at the cellular level. 3D printing with materials sourced from the patient's body eliminates the risk of organ rejection. These structures could one day even enhance our bodies' bionic capabilities, provide resistance to toxins, and add many desirable capabilities beyond the human body's natural limits.

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About the Author

Richard Horne (RichRap) is an electronics engineer, product designer, salesman, and technical problem solver. His professional work for the past 30+ years has spanned a wide range of industries and applications across many platforms and technologies. From arcade games to intelligent washing machines, Richard enjoys the technical and commercial challenges in any project and the satisfaction of designing products used by people all around the world.

Along with an obsession for all things 3D printing, Richard is a highly passionate advocate and supporter of open source, open innovation, and the wider *maker* communities. Richard joined the global RepRap project in 2009 and then continued to blog and share his ongoing developments and experience of 3D printing.

Dedication

I would like to dedicate this book to the life and passionate work of my friend, Sanjay Mortimer.



On November 27, 2021, Sanjay died at just 32 years old. Sanjay co-founded the 3D printing company E3D, and during his short life he managed to help revolutionize FDM 3D printing and bring multiple ideas, products, and innovations to the wider additive manufacturing industry. Almost every single desktop 3D printer available today, and many industrial machines, benefit from technology imagined and developed by Sanjay and the teams at E3D.

E3D has created a non-profit foundation for young adults with neurodivergent minds to help realize their potential through the field of engineering and making. If you wish to help, donate, or find out more about the Sanjay Mortimer Foundation (SMF), please go to the official website at www.sanjaymortimerfoundation.org/.

Sanjay, I will always remember you.

Acknowledgments

I would like to thank everyone who played a part in the making of this book. To my agent, Carole Jelen; editor, Paul Levesque; my wife and children; and the highly talented and professional team at Wiley, thank you all so much for the support, advice, and guidance. I'm truly delighted to be working with such a great team of editors and publishing experts. I would also like to thank the entire 3D-printing industry for being such a fantastic place to inspire innovation and build lifelong friendships.

Publisher's Acknowledgments

Acquisitions Editor: Elizabeth Stilwell

Senior Project Editor: Paul Levesque

Copy Editor: Kelly D. Henthorne

Tech Editor: Alex Gibson

Production Editor: Tamilmani Varadharaj

Cover Image: © Alexander Tolstykh/Shutterstock

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