

TECHNOLOGY IN ACTION™



# Mastering 3D Printing



A Guide to Modeling, Printing,  
and Prototyping

—  
*Second Edition*

—  
Joan Horvath  
Rich Cameron

Apress®

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Printed on acid-free paper

*For everyone who contributed to the RepRap  
project to start this revolution.*

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# About the Authors



**Joan Horvath** and **Rich Cameron** are the cofounders of Nonscriptum LLC, based in Pasadena, California. Since 2015, Nonscriptum has consulted for educational and scientific users in the areas of 3D printing and maker technologies. Joan and Rich find ways to use maker tech to teach science and math in a hands-on way, and want to make scientific research cheaper and more accessible to the public. This book is their eighth collaboration

for Apress. They have also authored additive manufacturing online courses for LinkedIn Learning (formerly Lynda.com). Links for all of these are on their website, [www.nonscriptum.com](http://www.nonscriptum.com).

In addition to her work with Rich, Joan also has taught at the university level in a variety of institutions, both in Southern California and online. Before she and Rich started Nonscriptum, she held a variety of entrepreneurial positions, including VP of business development at a Kickstarter-funded 3D printer company. Joan started her career with 16 years at the NASA/Caltech Jet Propulsion Laboratory, where she worked in programs including the technology transfer office, the Magellan spacecraft to Venus, and the TOPEX/Poseidon oceanography spacecraft. She holds an undergraduate degree from MIT in aeronautics and astronautics and a master's degree in engineering from UCLA.

## ABOUT THE AUTHORS



**Rich Cameron** (known online as “Whosawhatsis”) is an experienced open source developer who has been a key member of the RepRap 3D printer development community for many years. His designs include the original spring/lever extruder mechanism used on many 3D printers, the RepRap Wallace, and the Deezmaker Bukito portable 3D printer. By building and modifying several of the early open source 3D printers to wrestle unprecedented performance out of them, he has become an expert at maximizing

the print quality of filament-based printers. When he is not busy making every aspect of his own 3D printers better, from slicing software to firmware and hardware, he likes to share that knowledge and experience online so that he can help make everyone else’s printers better too.



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Much has changed from the first edition, but Diego Porqueras of Deezmaker, Metalnat Hayes, and Peter Dippell's invaluable inputs back then still echo in this edition. We also particularly thank Michelle Lowman, the editor of the first edition, for taking a chance on us back in 2014 when this was so new.

We talked to many 3D printing professionals and maker-educators as we worked on this book, and we are grateful for the advice, images, and in some cases permission to use screenshots or photographs of their work, credited in more detail in the text. We want particularly to call out Steve Wygant of SeeMeCNC; Shelley Sun of MAKEit, Inc.; Mara Hitner and Dave Gaylord at MatterHackers; Cody Casale of Casale Design LLC; Will and Jewelyn Co of CoKreerate; Nicole York of 3D Systems; Gabe Bentz of Slant 3D; David Shorey of Shorey Designs; Marius Kintel and the other OpenSCAD developers; and Ultimaker for allowing use of Ultimaker Cura screenshots. We are also grateful to the teams at Formlabs, SprintRay, The Virtual Foundry, and Procusini for discussions and images and to Desktop Metal and Markforged for insights for the metals chapter.

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# Introduction

We have been astonished at how much the 3D printing industry has changed since the first edition of this book, which was published in 2014. Amazingly little has remained constant since then, except perhaps for a sense of wonder about what might be possible. That sense now is informed by more sober realities about the challenges that remain, as well as more realistic ideas about good applications.

In this book, we want to give you a path to get started with 3D printing, as well as enough insight to go a considerable distance down the road to using it to create useful things. 3D printing still is not all that straightforward, and we have tried to create a balance between telling you enough so you can get started without drowning in too much detail and not telling you enough. We have minimized the use of step-by-step screenshots, for example, since those get out of date quickly. Instead, we have given a few examples and tried to tell you what we were doing and why, so that you can do the same thing in whatever system you are using.

3D printing now is largely a materials game. Whether you want to print in metal or plastic, and the mechanical characteristics of the final part, will drive the choice of printer type (filament, resin, or powder) and thus price point. Printer hardware design innovation continues. However, we expect to see faster evolution of materials that will allow seamless creation of a prototype and first production run with a 3D printer, then moving on to injection molding for high-volume parts. Dentistry has emerged as a key early adopter, along with general product prototyping and creation of tooling and fixtures.

We expect this book to be used by a wide spectrum of readers, from K-12 teachers to plant managers. As such we have included a variety of examples to give you ideas on what is possible. Since we have heard that

## INTRODUCTION

some people used the first edition as an ad hoc textbook, in this edition we include questions at the end of each chapter. If you are using this to learn on your own, you may find reflecting on the questions useful to focus your understanding as you go.

New in this edition is a discussion of printers that use liquid resin, which was far less ubiquitous in the consumer market in 2014 than it is now. By their nature and heritage, the many brands vary more among manufacturers than filament printers do, and we have accordingly tried to keep things generic but with enough information to get you started. We also dip into what is possible with powder-based printers, particularly those used to create metal parts.

The book is divided into three parts. Part 1 covers 3D printing hardware and software, starting with the basics of understanding when using a 3D printer is a good idea (Chapter 1), what technologies are generally available (Chapter 2), and the overall workflow and software environment for actually using a printer (Chapter 3). Chapter 4 discusses how to select a printer based on what types of parts you will want to print. Chapter 5 gets into how creating a print works, and what to do to resolve common problems. Chapter 6 winds up the section with a discussion about how to post-process a print so that it is suitable for its ultimate use.

Part 2 is focused on designing models to be 3D printed. Like all manufacturing techniques, it is possible to design a part that is easy or hard to fabricate with a 3D printer. Chapter 7 reviews common computer-aided design (CAD) software and the strengths and weaknesses of various types. Chapter 8 gives you some design rules for creating a part. Chapter 9 describes part geometries that require special handling.

Finally, Part 3 describes applications, starting with manufacturing plastic parts (Chapter 10) and moving from there into the many options for printing in metal (Chapter 11), some of which are surprisingly affordable. We wrap it up with chapters on visualization and prototyping (Chapter 12) including innovative uses in surgery planning, a discussion of 3D printing

in the classroom (Chapter 13), and wind up with a survey of applications in their early stages now (Chapter 14) like specialty food printing and bioprinting.

We hope you find the book useful and a jumping-off point to getting started or to going to the next level. At the end of Chapter 1, we have noted other resources we have created. We hope you will invent the next amazing application for future editions of the book.

# PART I

## 3D Printer Hardware and Software

In this section, we describe the available 3D printer technologies and their advantages and disadvantages and the basics of what you need to know to operate one. In Chapter 1 we cover the situations when one would want to use a 3D printer. Chapter 2 discusses materials available for 3D printing and how your material choice may drive your printer hardware selection. Chapter 2 moves on to cover the *slicing* software that takes a design and makes it printable.

In Chapter 4, we move on to helping you make a purchasing decision for your printer, and in Chapter 5 we walk you through how to actually operate it and troubleshoot common problems. We wind up Part I with Chapter 6's review of techniques to use on a finished print for cosmetic or functional reasons. You will then be ready to think about how to design something to print (Part II) and 3D printing applications (Part III).

## CHAPTER 1

# Why Use a 3D Printer?

3D printing has been around since the 1980s. It has exploded in popularity since key patents began to run out in the 2000s, and by the mid-2010s low-cost 3D printers were everywhere. In the ensuing excitement, there was a lot of hype and a sense that soon everyone would have a 3D printer at home and would manufacture some large part of their consumer goods.

Reality has turned out to be both more and less interesting than that. Learning to use a 3D printer requires two distinct sets of skills. First, a user has to be comfortable with computer-aided design (CAD) tools or have access to models created by someone else. 3D printers require that you have a 3D computer model of your object in an appropriate format. A photo or other 2D image is not enough, since you need to have data that is stored as a full 3D model of the object (although scanners that take many pictures from different angles can use software to create a 3D model from them).

Then, to actually print it, some understanding of the physical properties of the real materials and the structure of your part in the real world is needed too, so that it will not fall apart during printing. People often come in from one side of that divide or the other and are surprised by how much they need to learn to be successful. Software is starting to bridge some of that gap as the market expands.

The home market makes sense for people who are comfortable with computer-aided design and like to make things in general, and thus who have a less-steep learning curve to climb. However, professional manufacturing has started to embrace 3D printing in earnest. Needing skills in both design and fabrication is nothing new for a factory, and 3D printable versions of common materials are becoming available.

This means that factories can do one-off prototypes and small batches of product and then seamlessly jump to very high-volume traditional techniques only if there is proven demand. Lower-cost ways of 3D printing metal are becoming available too. Printing molds and fixtures can likewise replace other methods that are far more costly and time-consuming.

## Additive Manufacturing

3D printers create objects one layer at a time. The way they do that—by extruding melted plastic, by sintering materials, by hardening resin with UV light—can vary. But the basic premise is the same: a layer of material appears, controlled by a digital design stored in a computer, then another, and so on until the object appears, seemingly by magic. The key distinction from most other means of manufacturing is that 3D printing is *additive*—material is not cut away, but is added to a piece as it is built (Figure 1-1). Consumer-level 3D printers are very simple robots. We often say that they are, more or less, computerized hot glue guns (using a somewhat different plastic, though).

3D printing is a form of *additive manufacturing*. Additive manufacturing starts with nothing and builds up parts by laying up material on some sort of build platform. A lot of conventional manufacturing is *subtractive*, meaning that you start with a block of material (like metal or wood) and start cutting away material until you have the part that you want plus a pile of sawdust or metal shavings.





*Figure 1-1. A 3D print in progress*

## History of Robotic 3D Printing

Charles W. (Chuck) Hull is generally credited with developing the first working robotic 3D printer in 1984, which was commercialized by 3D Systems in 1989. These machines were systems that used a laser to harden liquid resin, and many machines still use this technology. Other early work was taking place at the Massachusetts Institute of Technology (MIT) and University of Texas.

A flurry of patents followed in the early 1990s for various powder-based systems. These systems use inkjets to deposit a binder very precisely on the surface of a bed of powder to create layers on a downward-moving platform. These inkjet 3D printing patents became the basis for Z Corp, now part of 3D Systems. Alternatively, a laser can be used to fuse powdered plastic or metal together, called *selective laser sintering (SLS)*.

Meanwhile, S. Scott Crump and Lisa Crump patented [fused deposition modeling \(FDM\)](#) in 1989 and cofounded printer manufacturer Stratasys, Ltd. This technology (more generically called FFF, for fused filament fabrication) feeds a plastic filament into a heated extruder and then precisely lays down the material. When key patents expired in 2005, this

technology became the basis of the RepRap movement described in the next section. This book mostly focuses on this type of printer, but we have some forays into resin stereolithography (SLA) printers and the various descendants of SLS as well.

## The RepRap Project

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

Furthermore, Bowyer decided he would put the designs for the parts for his 3D printer out on the Internet available to anyone with encouragement to others to improve them, with the requirement that anyone who wanted to distribute an improved version had to do so under the same license terms (an *open source* license). He called this concept the *RepRap* project, and obtained some initial funding from the UK's Engineering and Physical Sciences Research Council.

Bowyer's team called their first printer *Darwin*, released in March 2007, and the next *Mendel*, released in 2009 (for more details, see [http://en.wikipedia.org/wiki/RepRap\\_Project](http://en.wikipedia.org/wiki/RepRap_Project)). The printers were named after famous evolutionary biologists, because they wanted people to replicate the printers and evolve them as they did so. Files to make the plastic parts were posted online, freely available with alterations and improvements encouraged. Necessary metal parts were ideally available at a hardware store or able to be made in a garage. More exotic metal parts like gears to grip filament and nozzles to push it through became available for online purchase pretty early on from entrepreneurial printer builders with access to machine tools to make them. Stepper motors and some of the electronic components needed to drive them were already available online, but became much cheaper and easier to find as the 3D printer market increased the demand for them.

The early printers were difficult to put together and to get to print well. In the Czech Republic in 2010, Josef Prusa released a design now called the *Prusa Mendel*. It simplified the original Mendel design, and after that, there was an acceleration in printer designs as people tried out the open source designs, modified them, and posted their own. Prusa Research ([www.prusa3d.com](http://www.prusa3d.com)) is now one of the larger consumer 3D printer companies, still based in the Czech Republic.

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

## Crowdfunding and Makers

What really caused a blossoming of different designs, though, was the availability of funding for hardware projects through *crowdfunding*—websites that allow entrepreneurs to put out early-stage products and take contributions from the public to fund development and early production. Since the key patents had run out, entrepreneurs typically did not have any type of proprietary technology, which made traditional startup funding difficult to obtain.

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

On April 28, 2009, the *Kickstarter* crowdfunding platform was launched ([www.kickstarter.com](http://www.kickstarter.com)). Kickstarter is one of many *crowdfunding* platforms which allows an entrepreneur to post a project and ask people

to support the endeavor. Various crowdfunding platforms have different rules about the type of project that is acceptable, and open source 3D printers are a very good fit for crowdfunding because most crowdfunding sites require a clearly defined project. Developing a 3D printer is a project with a natural endpoint, and often people offer a printer as the reward the person gets for supporting the development.

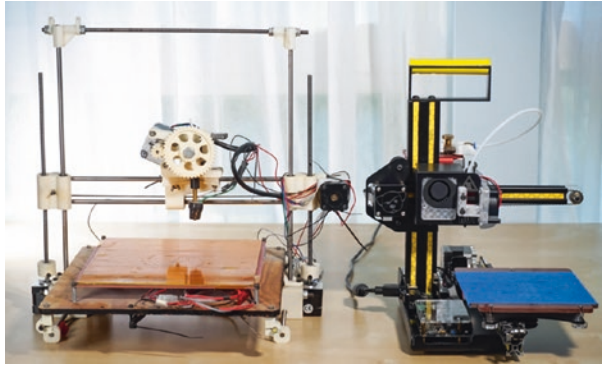
Since an open source printer, by definition, is not patented, it can be difficult to raise money in conventional investment forums. However, it is a good philosophical match for crowdfunding, extending the we-will-all-build-it-together open source ethos to also raise the money for launching a new 3D printer design.

In 2012, the *Form 1* stereolithography printer raised nearly three million dollars on Kickstarter. Many other 3D printers have raised in the six figures on Kickstarter and other platforms.

Figure 1-2 shows two RepRap heritage printers. Rich designed the 2011 RepRap *Wallace* (*a proof of concept machine, never sold commercially*) and was a key team member in the design of the 2013 Deezmaker *Bukito*, *which was launched on Kickstarter*.

At the same time that open source hardware was becoming common, open source or free software also began to stabilize and be useful to a nonexpert consumer. Software to design models and to prepare them for printing made great strides around this time. Today, some printers come with proprietary software, but printers that support generic protocols can use free or open source software end to end to create models and print them.

Figure 1-2 shows how rapidly open source printer design matured in a little over two years. Since then, many 3D printer companies have been started, and many have gone out of business or been acquired. Much of the actual manufacturing of printers and materials has moved to China and other lower-cost markets, and only a handful of companies that were around at the beginning of the consumer boom still exist.



**Figure 1-2.** *The RepRap Wallace (L) and Deezmaker Bukito (R)*

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**Note** One good outcome of this heritage is that many 3D printers run on the same software base as each other. This means that if you are used to one printer you will be able to learn others fairly easily, and there are some software packages that work for many of them. In this book we will focus on Ultimaker Cura, which works with many different printers, but you should be able to translate if you use one of the other packages. We have much more about this in Chapter 3.

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## Kit or Fully Assembled?

Up until about 2013 or so, most consumer 3D printers required at least some assembly. It was worth mentioning in marketing materials if the assembly did not require soldering, since kits in those days often consisted of bags of wires, screws, and small parts. Currently, kits usually require minimal assembly, typically involving tightening a few screws and plugging a few electrical connectors, all of which are clearly labeled and keyed to prevent you from doing it wrong. The cost can be a lot lower, since often printers have a few pieces that will fit well in a small package when disassembled, leading to lower shipping costs.

Obviously, though, if you are not comfortable with doing some assembly and calibration, you are likely to be happier with a fully assembled printer. Even this minimal assembly teaches you something about how the machine works, though, so you will be more likely to know how to fix something that goes wrong.

## When to Use a 3D Printer

3D printing is a very versatile technology, but there are times when other technologies are preferable. For example, laser cutters and small computer-numerically controlled (CNC) machines may be more appropriate tools in some circumstances. Of course, sometimes you can just use a piece of cardboard and an X-Acto knife to make something too.

Leaving that last one aside, we can do a comparison of the three common forms of *digital manufacturing*, machines that make something based on a computer file containing machine commands that result in a physical part. Laser cutters work from a 2D file (a .dxf or .svg format, typically) and 3D printers and CNC machines from 3D files in one of several formats (a common one for both being G-code) and manufacturer-dependent levels of interoperability among brands. All three have come down in price, although 3D printers probably have made the biggest strides there. The “maker movement,” a renewed interest in making physical things, has created a market for these machines, which then bubbled up into professional applications.

For the details on the 3D printer options, see Chapter 2 for different types of printer and Chapter 3 for software and workflow issues. Chapter 4 discusses criteria to use when buying one based on what you want to do. In a nutshell, one of the challenges with low-cost 3D printers (as well as most of the higher-cost ones) is that prints take a long time. A twelve-hour or even multiday print is not uncommon, which might mean you want a gang of printers if you are going to depend on them for production. Second,