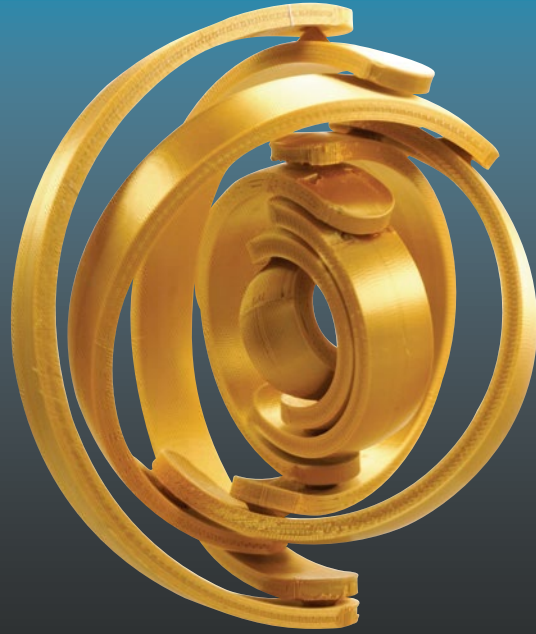


TECHNOLOGY IN ACTION™



# Mastering 3D Printing in the Classroom, Library, and Lab



Joan Horvath  
Rich Cameron

Apress®

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Printed on acid-free paper

*To the open source community, particularly to  
contributors to the RepRap Project, whose vision made  
consumer 3D printing a reality*

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# About the Authors

**Joan Horvath** and **Rich Cameron** are the cofounders of Nonscriptum LLC, based in Pasadena, California. Nonscriptum consults 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 seventh collaboration for Apress. They teach online classes in 3D printing and maker tech for LERN Network's U Got Class continuing education program. They have also authored online courses for LinkedInLearning/Lynda.com. Links for all of the above are on their website, [www.nonscriptum.com](http://www.nonscriptum.com).



In addition to her work with Rich, Joan also has an appointment as adjunct faculty for National University's College of Letters and Sciences. She 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.

## ABOUT THE AUTHORS

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.



Rich (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's 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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The consumer 3D-printing ecosystem would not exist in its current form without the open source 3D-printing hardware and software community. The maker community as a whole has also been very supportive. We appreciate how much we learn by looking at projects made by everyone at maker events large and small.

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We talked to many 3D-printing professionals and maker-educators to develop this book and we are grateful for the advice, images, and in some cases permission to use screenshots or photographs of their work, which is credited in more detail in the text. On the 3D-printing side of the family, we want to particularly call out Steve Wygant of SeeMeCNC; Shelley Sun and Russell Singer of MAKEiT, Inc.; Mara Hitner and Dave Gaylord at MatterHackers; Diego Porqueras of Deezmaker; Marius Kintel and the other OpenSCAD developers; the teams at Ultimaker and Formlabs; and Thatcher Chamberlain, Metalnat Hayes, Giovanni Salinas, and David Shorey.

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# Introduction

It has only been four years since the original 2014 *Mastering 3D Printing* went to press. In the intervening years, the field has exploded so much that we are focusing this book on the needs of the educational and scientific markets. Printers have dropped in price down to a few hundred dollars for a basic model and a few thousand for a fairly sophisticated one. Yet adoption has been remarkably slow in education, and we hope to change that.

This book focuses on consumer-level printers and their applications in the educational and scientific environments. We focus primarily on 3D printers that create objects by melting plastic filament, but also include a little about printers that use liquid resin.

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

This book is intended for several audiences. It is meant to be a self-contained tutorial on consumer 3D printers and the open source software that runs them, particularly for educators who are trying to set up or run a school makerspace or librarians who are trying to figure out what to do about a mandate to buy printers or create a community space.

Although we say the book is for “classroom, library, and lab,” a broader audience will find the core information helpful. If you are not an educator and want to focus on the 3D printing per se, Chapters 1–6

## INTRODUCTION

apply to anyone's use of consumer-level printers; Chapter 8 gives a lot of information on post-processing prints to make them look good; and Chapter 9 discusses making prints as strong as possible. The examples in the other chapters, although primarily classroom oriented, may inspire you for your projects as well.

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

Part I (Chapters 1–3) of the book gives background on the history of 3D printers, talks about how the hardware and software work, discusses available materials, and gives some detail of the 3D-printing workflow.

Part II (Chapters 4–6) reviews how to decide what kind of printer you need to buy, based on what you want to build with it and what materials you think you will want to be able to use. This part also reviews what kinds of facilities different 3D printers require, and the hands-on details of dealing with issues that might arise during a print. Finally, this part reviews options you can use to create 3D-printable model files.

Part III (Chapters 7–12) discusses the classroom use of 3D printing in different subject disciplines, with a particular focus on K–12. We start off with a brief introduction to common issues in classroom 3D printing, and then look at art and theater concerns, considering print post-processing topics like gluing, sanding, and painting, as well as a bit about casting jewelry. We also consider engineering concerns, like making a print strong enough for a functional job. Next, we take up using printers in language arts and social studies, and in the elementary school environment. Finally, we talk about how 3D prints might help special-needs students, particularly the visually impaired.

Finally, in Part IV (Chapters 13 and 14), we discuss university and community uses of 3D printing and how to think about careers in 3D printing in the near and long term. Chapter 13 focuses on research into both applications of 3D printing and technology development for 3D printers per se. Chapter 14 winds up the book with a discussion of the opportunities and challenges for teaching entrepreneurship, and tries to predict where the manufacturing and other applications of the technology are likely to be in the near and longer term.

We also include an appendix, in which we have gathered all the links from the book, plus a few news sources that cover the 3D printing world and some books that might provide other places to explore.

Librarians will likely find Chapters 1-6 and 13-14 the most useful, although the materials in Chapters 7-12 may suggest community projects.

The field is still evolving. As in the 2014 *Mastering 3D Printing*, we have avoided detailed descriptions of software packages. We stick with descriptions that will let you get started but will not be wrong three months after publication. We like to say that 3D printing is about as complex as cooking. In cooking terms, you will find that this book has a bias away from providing recipes to follow exactly and instead leans toward teaching you how to cook using your own judgement for the long haul.

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

# PART I

## 3D Printing: State of the Art

In Part I (Chapters 1–3) we introduce you to 3D printing and discuss why you may want to use a 3D printer instead of other digital manufacturing tools, like laser cutters or computer numerically controlled (CNC) milling machines. We cover the basics of printer technologies. These days, which materials you want to use and what types of things you want to build will drive your choice of printer, and we detail the issues in Chapter 2. Finally, in Chapter 3 we introduce you to the overall workflow of 3D printing and discuss the details of using “slicing” programs to create 3D-printable files.

## CHAPTER 1

# Why Use a 3D Printer?

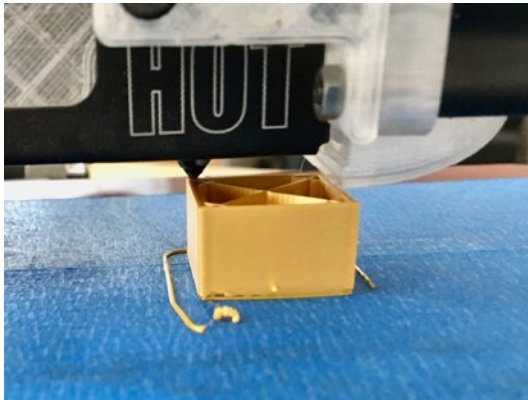
In the last five years, 3D printing has gone from a technology hyped as capable of solving any problem to one of disillusionment as people realized it took more expertise than some advertisements implied. Now machines are getting both easier to use and more powerful, and there is a creative explosion in both printer technology and applications. But we are still not quite at the point of clicking Print without any thought on the user's part.

In this book, we attempt to give you a clear-eyed view of the state of the art in 3D printing: what you can do, what you might be able to do soon, and what you really do not want to do, at least not yet. This chapter focuses on when you want to use a 3D printer, and, perhaps more importantly, when you do not. The most fundamental question is: when do you want to use a 3D printer in the first place?

## Subtractive vs. Additive

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 is created, controlled by a digital design stored in a computer, followed

by another layer, 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).



**Figure 1-1.** A 3D printed part in progress

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*, which 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 you want plus a pile of sawdust or metal shavings.

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—you need to have data that is stored as a full 3D model of the object. We talk about this in depth in Chapter 6. (Although Tinkercad and other software discussed in Chapter 6 can “extrude” an image to make a “2.5D” raised version of a drawing.)



## Nature's 3D Printers

3D printing seems like an advanced technology, but many organisms and natural processes have been doing the equivalent for eons. Many rock formations in the southwestern United States were laid down when ancient oceans built up layers of silt. The resulting sandstone has since been carved away by wind, rain, and plant roots. Figure 1-2, taken in Zion National Park in Utah, is an example of the current state of processes that build up material a layer at a time and then erode some of it away. This is a mix of an additive process (like 3D printing), followed by a subtractive process (like conventional manufacturing).



**Figure 1-2.** Sandstone layering (Zion National Park, Utah)

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

## 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 the University of Texas.

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. This book mostly focuses on this type of printer, but we go on some forays into resin stereolithography (SLA) printers as well.

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. By adding ink to these binders, this process can make full-color prints.

These inkjet 3D-printing patents became the basis for Z Corp, another early printer company that created large industrial printers. Z Corp is now part of 3D Systems. Other powder-based printing technologies manufactured by 3D Systems and others use a laser to fuse powdered plastic or metal together in a process called *selective laser sintering* (SLS).

## The RepRap Movement

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, making them available to anyone and encouraging others to improve them—with the requirement that anyone who improved it had to post their versions with the same terms (called 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 one, *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 hardware stores or could 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 is now one of the larger consumer 3D-printer companies, still based in the Czech Republic. You can look at a “family tree” of this period at [http://reprap.org/wiki/RepRap\\_Family\\_Tree](http://reprap.org/wiki/RepRap_Family_Tree).

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

## Crowdfunding and Makers

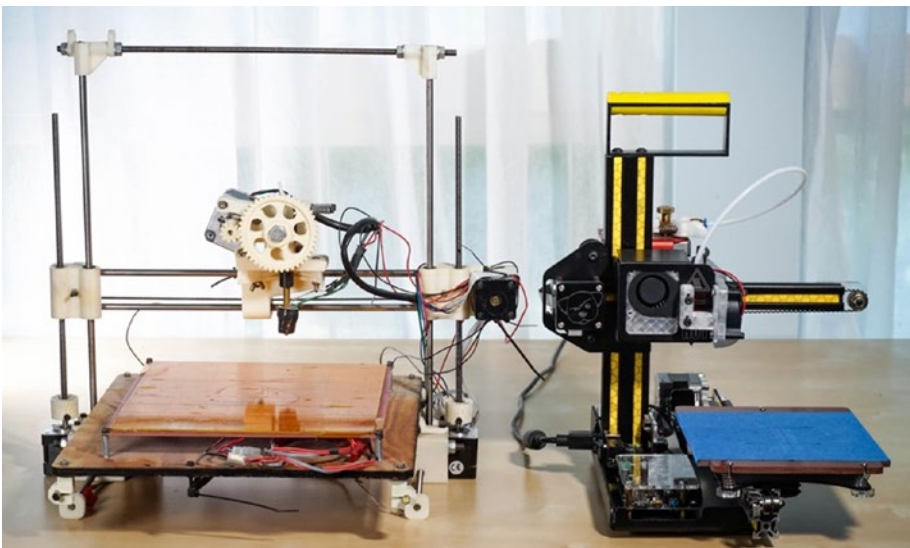
What really caused a blossoming of different designs, though, was the availability of funding for hardware projects through *crowdfunding*—websites that allow entrepreneurs to put out early-stage products and take contributions from the public to fund development and early production. Because the key 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 developers split into two main camps: those supplying large, industrial printers (typically with some proprietary technology) and a big informal network of people working on open source RepRap or similar filament-based consumer printers.

On April 28, 2009, the *Kickstarter* crowdfunding platform launched ([www.kickstarter.com](http://www.kickstarter.com)). Kickstarter is one of many *crowdfunding* platforms that allow an entrepreneur to post a project and ask people to support the endeavor. Various crowdfunding platforms have different rules about which types of projects are acceptable, and open source 3D printers are a very good fit for crowdfunding because most crowdfunding sites require a clearly defined project. Developing a 3D printer is a project with a natural endpoint, and often the developer seeking funding offers a printer as the reward for those who support the development.

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 1-3 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.



**Figure 1-3.** *The 2011 Wallace and 2013 Bukito*

At the same time that open source hardware was becoming common, open source or free software also began to stabilize and become useful to a non-expert consumer. Software to design models of 3D printers 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.

It is quite stunning to look at Figure 1-3 and see how rapidly open source printer design matured in a little over two years. Of course, innovation does not stop. In the intervening years, many 3D-printer companies have been started, and many have gone out of business or been acquired. This tumult is typical of a new industry and probably will continue for a while. In Chapters 4 and 5, we talk about how to select a printer for your needs and how to set up a good workflow. For the most part, we have tried to avoid naming brand names because the industry is still changing rapidly.

The pace of development in the field is very rapid; new methodologies are being invented both by commercial companies and by academics, and it can be a real challenge to keep up with it all and distinguish between a new capability and a dubious idea. The reach of consumer-level printers has expanded beyond maker hobbyists to more commercial applications. We discuss the opportunities and limitations in later chapters.

## **A Word About Kits**

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 some keyed and labeled electrical connectors in to the appropriate ports. The cost can be a lot lower than buying a fully