LEARNING MADE EASY

2nd Edition

3D Printing

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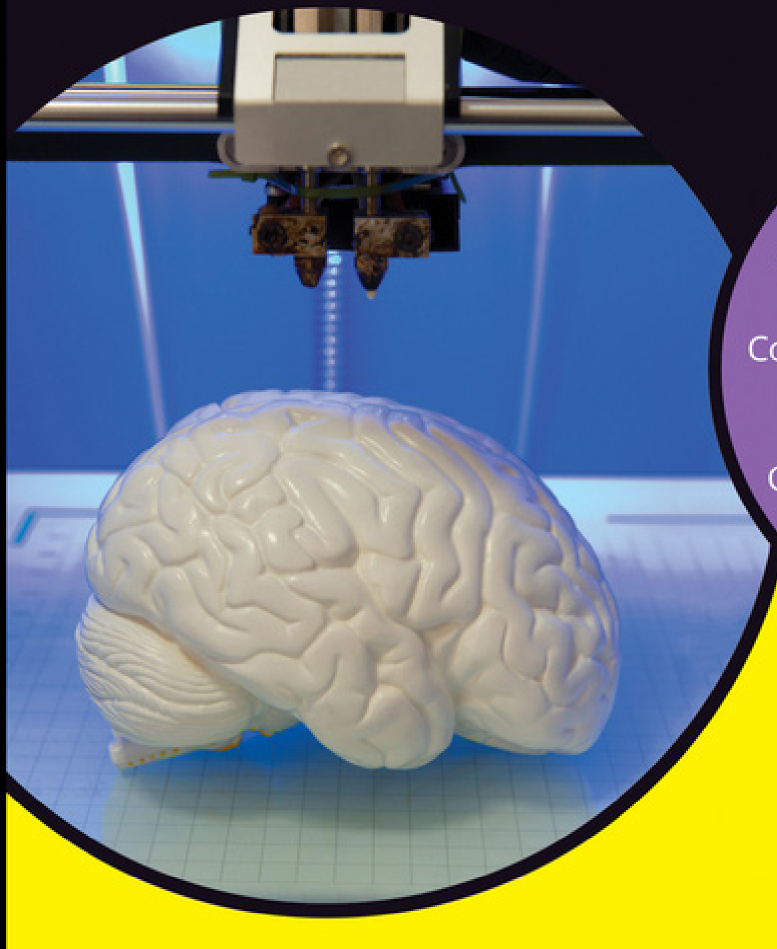

Review 3D-printing technology available today

Construct a RepRap 3D printer using open-source designs

Get strategies for successful 3D printing

Richard Horne

Kalani Kirk Hausman

3D Printing

2nd Edition

by Richard Horne and
Kalani Kirk Hausman

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3D Printing For Dummies®, 2nd Edition

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Contents at a Glance

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Introduction

3D printing has been around for more than 30 years. Recently, the core technology for 3D printers has become 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 comprised of subassemblies can be manufactured in a single run, whereas previously, they could not be made by traditional means. This process often improves the performance of the finished part.
- **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 actually 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. There are often still vastly better ways to produce many things without 3D printing.

Much of the media hype surrounding 3D printing was exactly that: hype. But the end of the hype cycle is near, and 3D printing is stronger than ever. Some 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, 2nd 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, we review many current additive manufacturing technologies. Some are early uses of a technology or process with numerous limitations and caveats regarding their use. We also explore the process by which you can build your own 3D printer, using the open-source self-replicating rapid-prototyper (RepRap) family of designs. This book won't make you an expert in all aspects of 3D printing, but it will give you an opportunity to explore additive manufacturing systems. We hope that you'll be excited by the amazing potential of 3D printers — excited enough to build your own printer and start sharing your creativity with friends and family!

As we updated this book for the second edition, we were pleased by the number of times we could change a statement from something like "NASA is planning to take 3D printers into space" to "NASA has now successfully tested and 3D-printed spare parts in space."

Foolish Assumptions

You may find it difficult to believe that we assumed anything about you; after all, we haven't even met you! Although most assumptions are indeed foolish, we 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 we review in this book. (You don't need to have a computer to enjoy this book, however. All you need are an open mind and enthusiasm about the future and what additive manufacturing can produce.)

- If you want to assemble a 3D printer of your own, you need to be familiar with using hand tools like spanners and screwdrivers. 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 are 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 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 ink-jet 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 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 materials and produce a higher level of detail in the finished parts.
- We also don't expect you to know all about product design or the fundamental properties of materials. Where possible we 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 that 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 build 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 about 3D printing.

We have listed various 3D printers, control electronics, and aspects about the assembly of a RepRap 3D printer of your own. We also include common terms used by the software used in 3D printing and the definitions of common settings used by the model-processing software. This should all assist you to get familiar 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 we think that you'll find interesting and amazing items on each page. In any event, we 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 alternatives available today.

Examine alternatives currently in existence for 3D printing.

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

IN THIS CHAPTER

» 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 products to food, 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 Industrial Age and then brought light and electricity to our homes and businesses.

New forms of manufacturing will give rise to new industries and allow for more recovery of materials. Like any truly fundamental change that spans all aspects of the global economy, by its nature, the change will be disruptive. But traditional, inefficient ways of producing new models of products will surely give way to new opportunities that were impossible to imagine before. The technology behind this transformation is referred to as *additive manufacturing*, *3D printing*, or *direct digital manufacturing.* Whatever you call this technology, in the coming decade, 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. (See Figure 1-1 for a glimpse.) Hold on tight, because in the chapters ahead, we cover a lot of incredible, fantastic new technologies — and before the end, we show you how you can get involved in this amazing transformation by building and using a 3D printer at home.

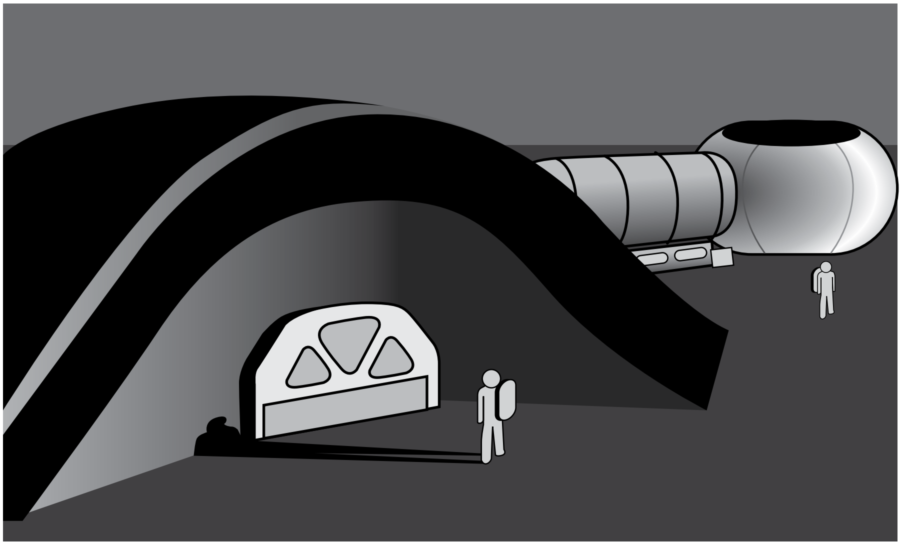

FIGURE 1-1: A line drawing of NASA's planned 3D-printed lunar facility.

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.

TIP

3D printers are much like the familiar desktop 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 from a variety of materials rather than producing a simple 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 reimagines a 3D object as a series of stackable layers that forms the finished object (see Figure 1-2). 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.

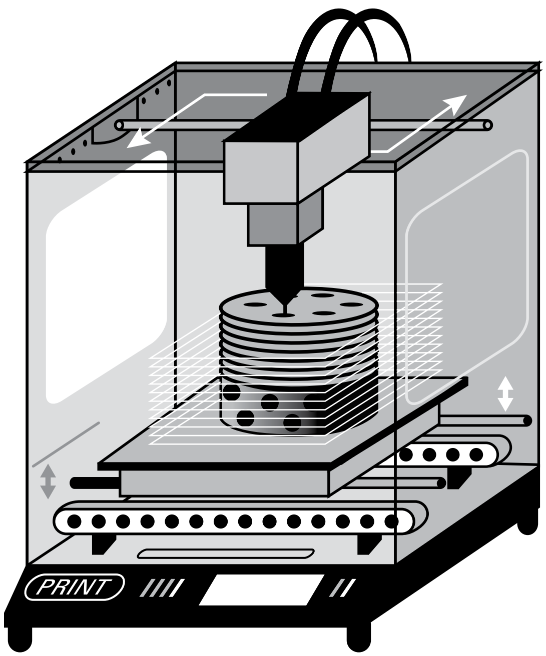

FIGURE 1-2: A line drawing showing how 3D printing works.

Kirk's children were building things this way before they ever saw his first 3D printer. They discovered that they could use crackers and cheese spray for more than just a snack: They could build towers and grand designs simply by layering crackers and cheese. These edible structures show the potential in additive manufacturing. Each cracker was given a personalized application of cheese to spell names, draw designs, and even build shapes and support tiny pyramids. The resulting snacks were both unique and customized to the design each child wanted.

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 spray. 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 layer at a time. 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 suggests that wires will soon become part of the additive manufacturing process, being printed directly in an object instead of being installed later.

Contrasting with traditional manufacturing

How does this 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?

Today, we stand at the opening moment of the next transformation: a third Industrial Revolution, in which mass manufacturing and 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 had to pass laws 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. 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 that 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 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 molds or through tooled dies at a foundry. This same technology was adapted to create plastic goods: Melted plastic is forced into injection molds to produce the desired product. Molding 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 midprocess 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.

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 we discuss in later chapters.

The iPhone case for the version 6/7 is downloadable as Thing 67414. (See Figure 1-3.) 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 (`http://www.thingiverse.com`). These improvements were rapidly shared among members of the community, who used them to create highly customized versions of the case, and Nokia gained value in the eyes of its consumer base through this capability.

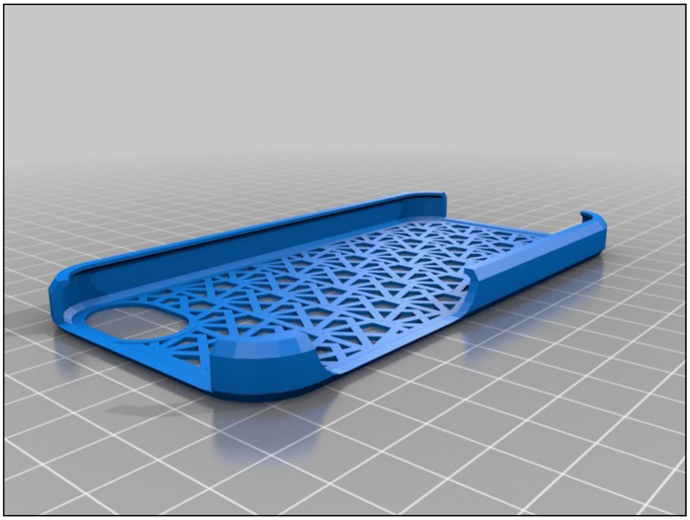

FIGURE 1-3: A free downloadable, 3D-printable phone case for the iPhone.

TECHNICAL STUFF

Creative Commons licensing 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.

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.

TECHNICAL STUFF

Additive manufacturing allows the use of a variety of materials in many components, even the melted plastic used in printers such as the RepRap device we show you how to build later in this book. 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 or beets. Current research on producing industrial quantities of this material from algae may one day help reduce our dependence on petrochemical-based plastics.

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 1-4.)

FIGURE 1-4: 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, 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.

Exploring the Applications of 3D Printing

Without doubt, additive-manufacturing technologies will transform many industries and may even return currently outsourced manufacturing tasks to the United States. 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, crowdfunding, robotics, ad-hoc media 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, we 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. We show you the types of materials that can be used in additive manufacturing, and we provide some ideas about the materials that may soon become available. We 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.

Whether you use a 3D-printing service or a home printer, you should take several considerations into account before creating your own 3D-printed objects, and we look forward to sharing these considerations with you.

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 used 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 system.

In Part 5, we show you how to assemble your own RepRap, configure it, and use it alongside free open-source software to build many items, including another RepRap 3D printer.

IN THIS CHAPTER

» 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. The RepRap printers we show you how to build 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.

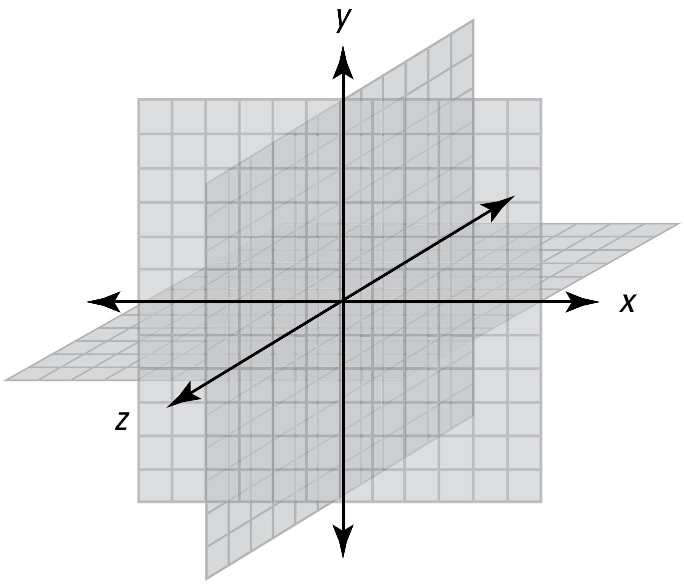

FIGURE 2-1: Cartesian coordinates using X-, Y-, and Z-axis notation.

These Cartesian 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

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 leads 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.

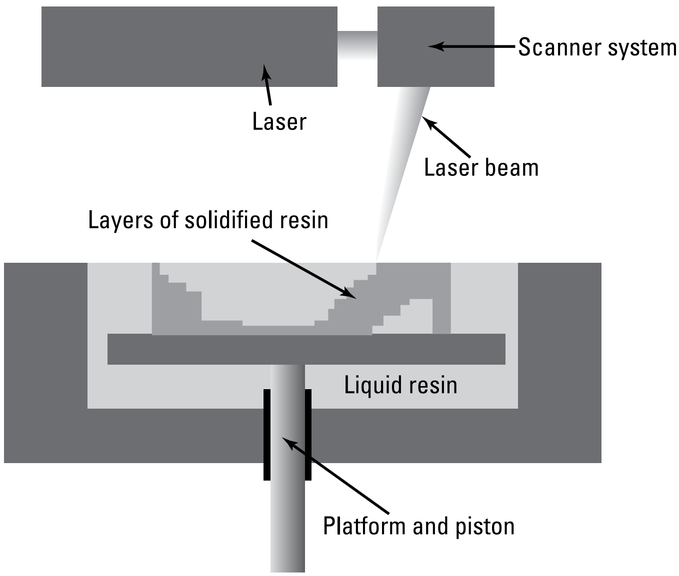

FIGURE 2-2: How stereolithography works.

Stereolithographic formation of objects provides excellent detail (see Figure 2-3), but the materials are currently limited to polymers that can be cured to solid states under focused light. 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.

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

High-resolution variations of stereolithography use lasers focused so tightly that individual elements of the final object are microscopic. Such multiphoton 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.

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.

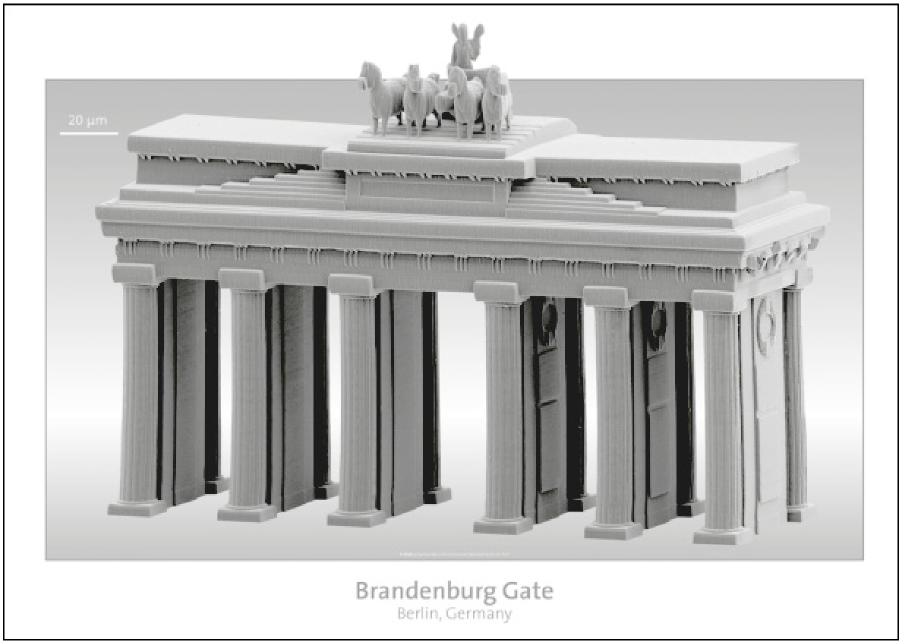

FIGURE 2-4: Object created via multiphoton lithography on a NanoScribe 3D printer.

Image courtesy of NanoScribe

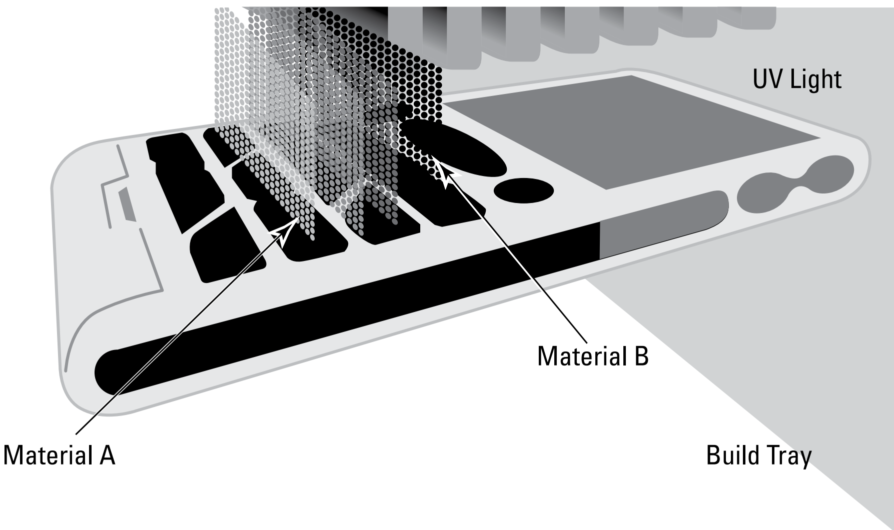

FIGURE 2-5: Objet's photopolymer PolyJet printer can mix multiple types of materials.

TECHNICAL STUFF

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)

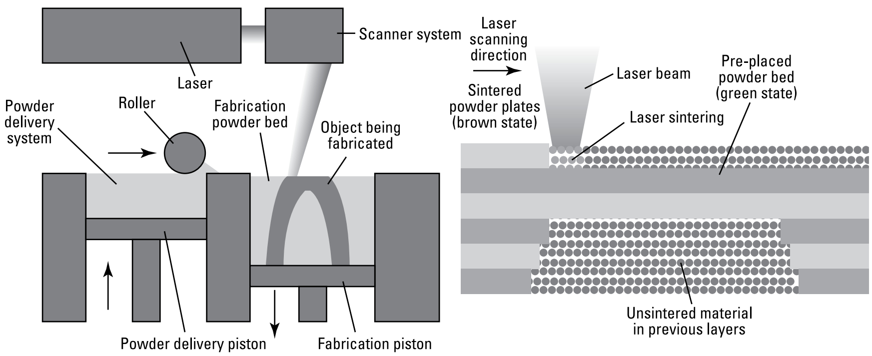

FIGURE 2-6: Laser powder sintering.

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). If the final object exceeds the build volume of the printer, final assembly can take place.

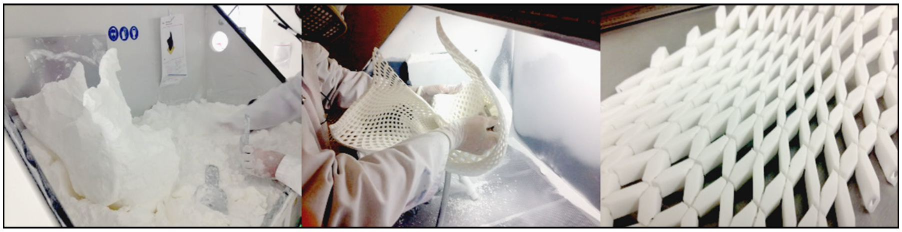

FIGURE 2-7: Extracting a piece of 3D-printed clothing from a granular binding powder bed.

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 conveyer 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 conveyer 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. 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.

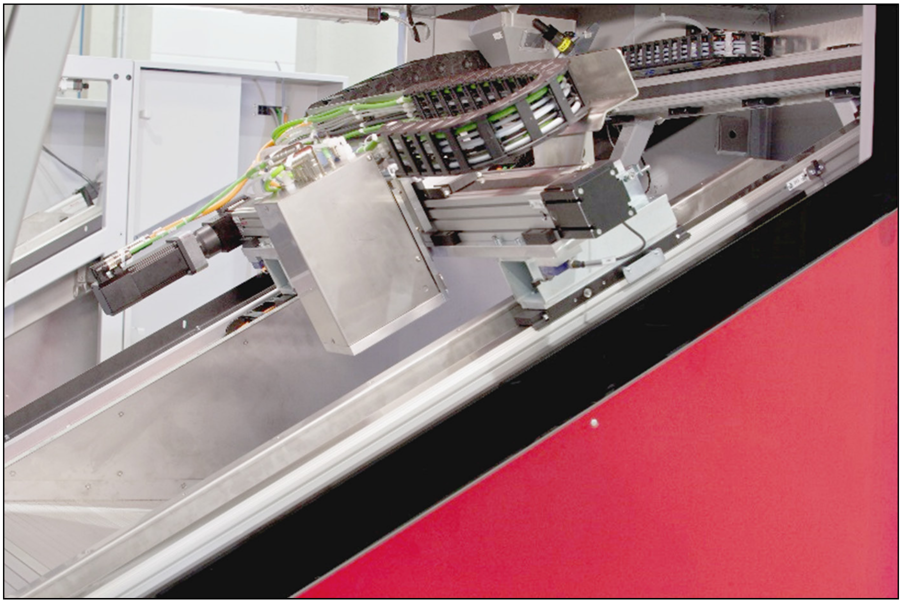

Image courtesy of VoxelJet

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

Image courtesy of WithinLab

"WELDING" IN SPACE

In space, the lack of gravity precludes the use of powder bed printing; blowing powder would create a small, unwanted form of exhaust. NASA has been investigating a close relative of blown-powder 3D printing that carefully injects wire into the electron beam. By using metal wire (as used in terrestrial electron-beam welding systems), researchers have performed additive manufacturing without gravity or atmosphere — and without the hazard created by the dispersion of metal powder into the cabin's air supply.

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, as illustrated in Figure 2-10.

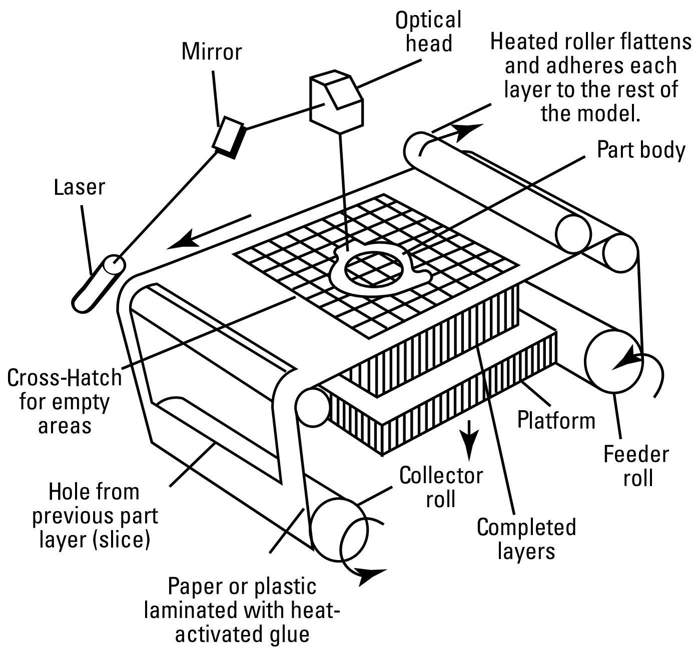

FIGURE 2-10: Laser-cut layers of plastic or paper combined with a heat-activated glue.