

- » 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.

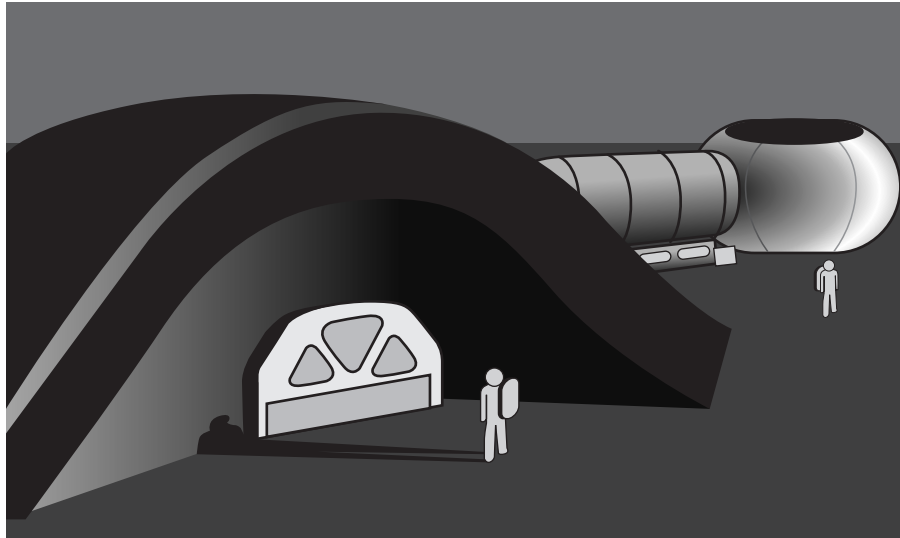


FIGURE 1-1:
A line drawing of
NASA's planned
3D-printed lunar
facility.

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.

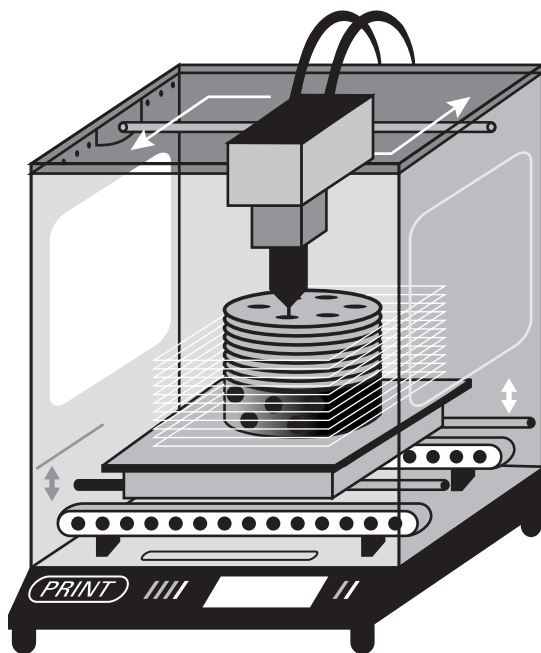


FIGURE 1-2:
A line drawing
showing how 3D
printing works.

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.

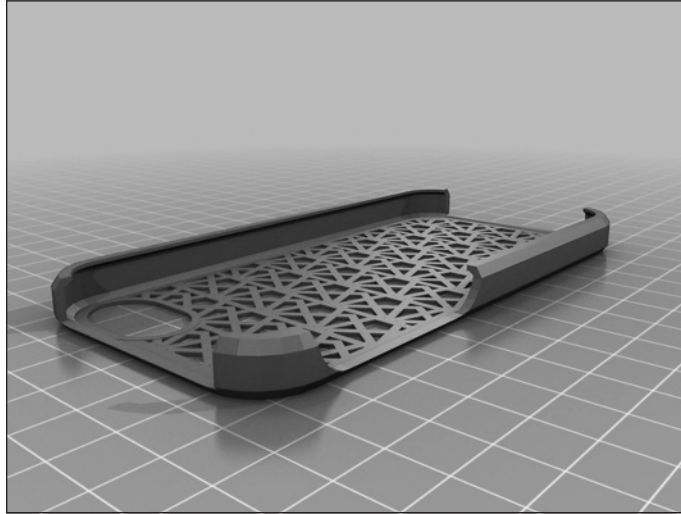


FIGURE 1-3:
A free downloadable, 3D-printable phone case for the iPhone.



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.



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.