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Chapter **1**

Seeing How 3D Printers Fit into Modern Manufacturing

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



TIP

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

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

Embracing Additive Manufacturing

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



TIP

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

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

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

Defining additive manufacturing

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



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

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

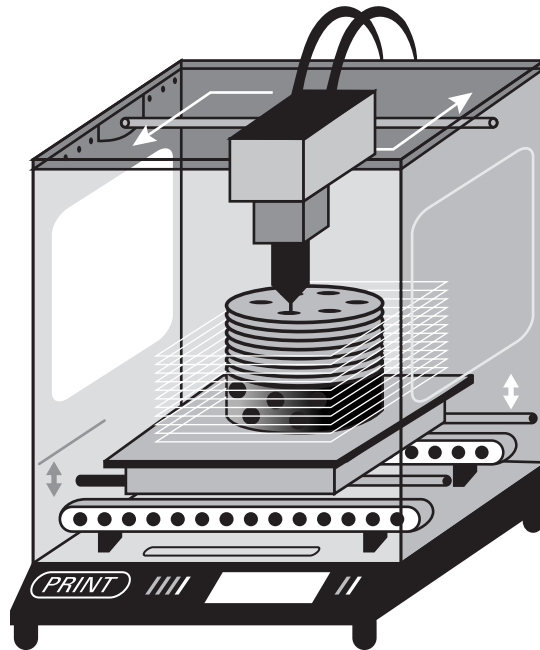


FIGURE 1-1:
A line drawing
showing how
3D printing
works.

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

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

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

Contrasting additive manufacturing with traditional manufacturing

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

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

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

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

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

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

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

Machining/subtractive fabrication

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



TIP

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

Molding/injection molding

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

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

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

Understanding the advantages of additive manufacturing

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

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

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

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

Personalization

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

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

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

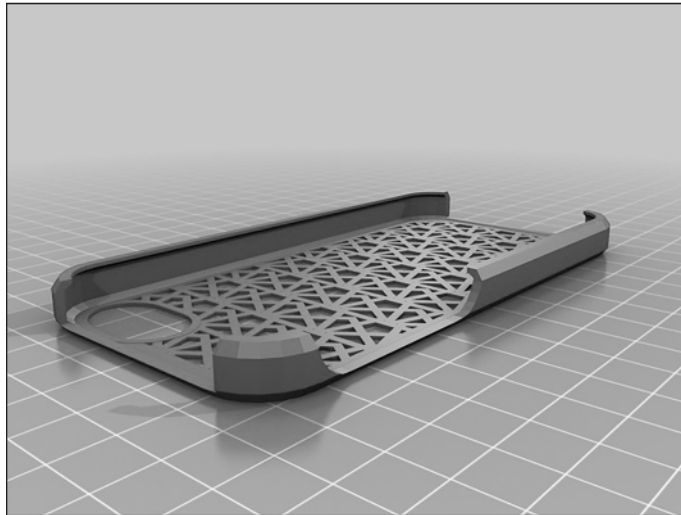


FIGURE 1-2:
A free downloadable, 3D-printable phone case for the iPhone.



TECHNICAL
STUFF

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



TIP

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

Complexity

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

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

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

Sustainability

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



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

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

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



Image courtesy of Markus Kayser

Recycling and planned obsolescence

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

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

Economies of scale

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

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

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

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

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

WORKING WITH RepRap

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

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

Exploring the Applications of 3D Printing

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

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



REMEMBER

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