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Hot off the Press: The Technology Behind 3D Printing

Introduction

Although engineers and scientists have been using 3D printing (3DP) for decades, the technology is only just beginning to filter into the popular consciousness almost thirty years later. Presented by Charles W. Hull in 1986[1], the technology was initially restricted to the creation of rapid industrial prototypes rather than final products, since the first 3D printers were costly, slow, and highly restricted in the types of materials they could use[2]. However, the increasing accuracy and range of printers created in the past decade, as well as plummeting costs, have shifted this trend: as of 2011, 20% of the output of 3D printers is now final products, with predictions that it will rise to 50% by just 2020[3]. There are also expectations that 3D printing will move into the private sphere, as companies like MakerBot release DIY printers for a mere $1,500[4].

3DP's have a number of advantages over more traditional "subtractive" manufacturing. The additive process requires less raw material and, because software (rather than hardware) drives 3D printers, each item can be made differently without costly retooling[3]. The printer can also produce remarkably intricate products that cannot be constructed easily in other ways, including movable parts, hinges, parts within parts, and porous structures. This may actually abolish the need for manual assembly in factories. Overall, 3D printers have the tremendous potential to transform our economy from costly mass-production to inexpensive mass customization. It will be as cheap to create single items as it is to produce thousands and thus undermines economies-of-scale. Finally, increasingly diverse disciplines are finding innovative uses for these printers, including art, architecture, engineering, aviation, medicine, and manufacturing.

Figure 1. MakerBot's Thing-O-Matic 3D printer, which is sold to private users for a mere $1,5000. It fits comfortably on a desktop. From REF 4.

How it Works

Three-dimensional printing (3DP) functions by building parts in layers. From a computer-aided design (CAD) model of the desired part, or a scanned 3D image, a slicing algorithm draws detailed information for every layer (typically 5-10 layers/mm)[5], which is then fed to the printer. Typically, this CAD will be modified to include internal braces and other supports that may be needed during the process. Each layer begins with a thin distribution of some material over a flat bed, either in liquid or powdered forms—typically metal, plastic, ceramic, or a photopolymer. This first layer is subsequently solidified by the application of one of the following: a liquid binder, laser sintering, or UV light. The solidification method and the raw material are largely what distinguish one printer type from another. A piston that supports the flat bed and the part-in-progress lowers by a fraction so that the next layer can be spread and selectively joined. This layer-by-layer process repeats until the part is completed, including all of the supports. Generally, the thinner the build-layer, the more accuracy and resolution is provided.

Depending on the printer, further processing may be required to cure the object. The speeds of different printers are mostly comparable, taking approximately 15-30 seconds per layer[1].

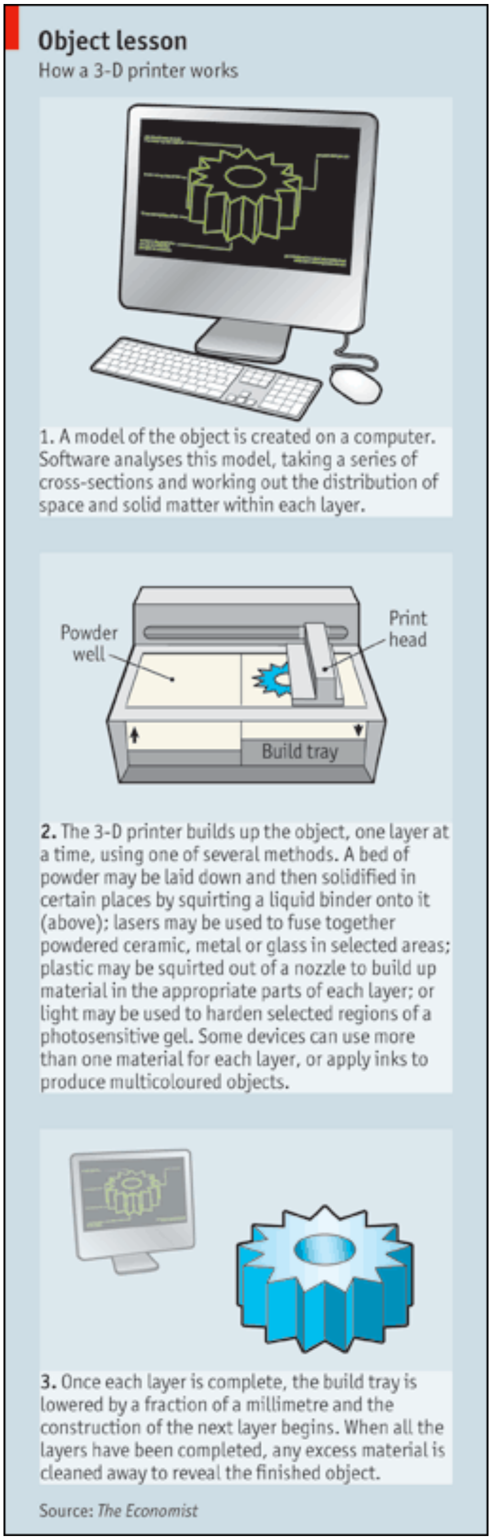

Figure 2. An overview of 3D Printing Technology. *From REF 1.*

Types of 3D Printers

Stereolithography Apparatus (SLA)

This is the oldest technique in 3D printing. The stereolithography apparatus (SLA) positions a perforated platform just below the surface of a vat of liquid (usually acrylic-based) photocurable polymer[7]. An intense ultraviolet (UV) laser beam then traces the first slice of an object on the surface of this liquid, causing a very thin layer to harden. The perforated platform is lowered slightly into the vat and a sweeper re-coats the solidified layer with liquid. The surface is again exposed to a UV laser, creating the next layer of the object. Once the product is printed, the excess soft resin is removed with a chemical bath, it is freed of support structures, and finally cured in a UV oven[6]. Stereolithography has the advantage of using a large range of photopolymers, from flexible rubber-like material to more rigid polymer, as well as producing a high level of detail and a very smooth surface finish.

Although this type of printing is highly accurate and has a minimum thickness layer of only 0.06 mm, SLA has some disadvantages: it does not support color, and the secondary structures have to be removed by hand[12]. Both of these flaws require prolonged post-processing, driving up costs and build time. Finally, stereolithography is rather expensive: machines cost approximately $250,000, while the photopolymer can be approximately $800/gallon[6]. The machine also has to be vented because of fumes created by the polymers and the interaction between polymer and solvent[6], rendering it inappropriate for home and office environments.

Fused Deposition Modeling (FDM)

Like SLA, FDM uses a liquid medium rather than powder. Inside a temperature-controlled print head, filaments of thermoplastic are heated to a semi-liquid state. They are then extruded in the x-y plane, layer by layer. The platform is maintained at a lower temperature, so that the thermoplast quickly hardens upon contact. The melted layers fuse together as they are added[7]. This material is typically either ABS plastic or polycarbonate, the latter producing especially durable and rigid end products[13]. Supports are built along the way with a second, weaker material, typically water-soluble plastic. The finished product does not require curing to harden, but it must be transferred to a warm bath to dissolve away the supports, requiring a water feed and drain. This process typically produces layers 0.13-0.25 mm thick, so products can suffer from a "stair-stepping" effect and a rough finish[8].

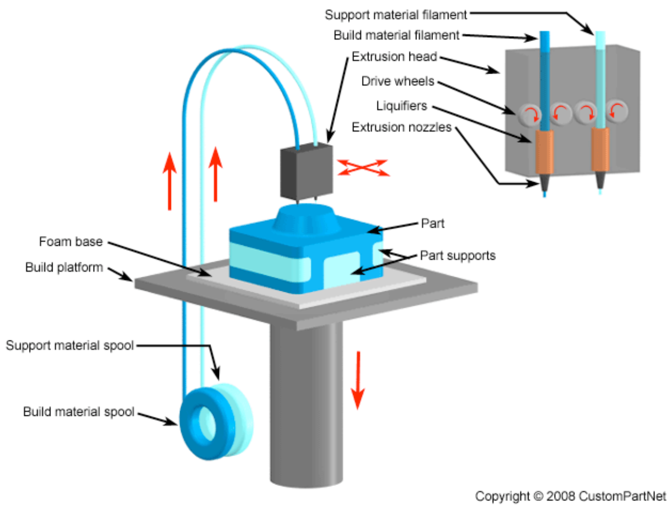

Figure 3. Schematic of the FDM technology. Material is fed into a temperature-controlled print head. Nozzles then extrude the material as the print head moves in the x-y plane. From REF 18.

FDM has the advantage of not requiring supports to be broken by hand, which reduces labor and cost, while the solvent method allows more intricate movable parts to be produced. It also accommodates color, although typically only one color per print job. It is relatively inexpensive, with machines costing between $15,000 to $30,000, and the MakerBot company has recently released an at-home version costing only $1,500[9]. However, because personal models can typically only use ABS plastic, their finished products may not be suitable for high heat, such as creating microwave-safe dishes.

3-D Inkjet Printing

MIT patented this process in 1993[5]. First, the machine fills the build chamber with a layer of powder—metal or plastic—so that the parts, when finished, rest on this powder for easy removal. The machine then deposits additional powder in 0.1 mm layers. The inkjet print carriage moves across this layer, depositing binder (and various inks for a color model) in the pattern of the slice as designed by the CAD model. The binder solidifies the powder, leaving the rest of the powder dry for recycling. The piston then lowers the flat bed by 0.1 mm and the process repeats. When finished, the model is suspended in powder to cure. The dry powder is then suctioned back into the hopper, where it is kept for the next printing job. Post-printing processing can include the use of an infiltrant, a secondary resin material that is typically drizzled or brushed onto the surface of the model. It fills microscopic pockets in the model, sealing its surface, enhancing color saturation, and improving the mechanical properties as it cures.

Inkjet printers may represent the most cost-efficient form of 3DP technology, since there is no need to waste material on additional supports, as loose powder performs this function. Moreover, because this powder is then recycled at the end, there is very little resulting waste. For some products, a salt water cure is sufficient, eliminating the need for costly solvents. ZCorp estimates a cost of approximately $0.12-$0.18 per cubic centimeter[10]. Lastly, inkjet technology provides full color printing and high accuracy, delivering details as small as 0.1 mm and structural walls as thin as 0.5 mm[10].

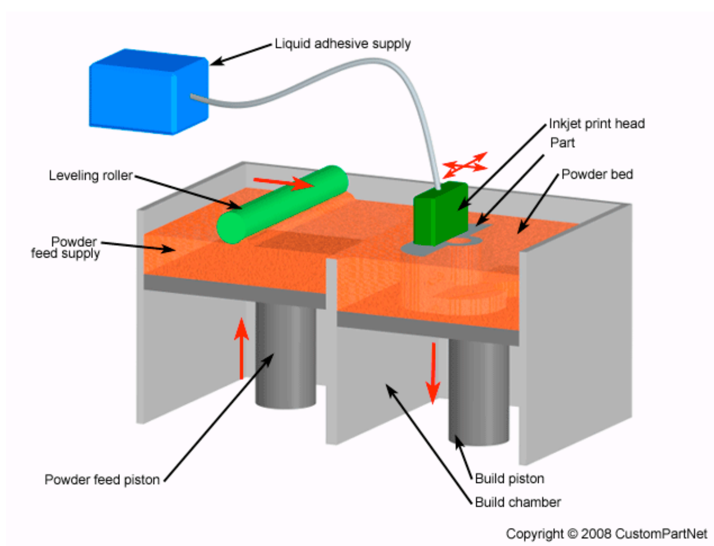

Figure 4. Schematic of inkjet printing. A powder feed supply deposits even layers of raw material, which is then solidified by liquid binder sprayed from an inkjet printer head. From REF 18.

Polyjet
This is a modified version of inkjet printing, in which the sliding print heads deposit very thin layers of two types of liquid photopolymer. One type is used for the cross-sections, while the other type is used to create supports. After the layer is printed, a UV light-source within the print head hardens the polymer in areas that need to be solid, and causes the support polymer to assume a gel-like state. The process is repeated until all layers are complete. At the end, water-jetting is used to wash away the supports. The machine is capable of making objects out of multiple kinds of solid photopolymer, each with different colors or properties. Polyjet technology is currently among the most accurate kinds of printing, as it can make layers as thin as 16 microns and walls as thin as 600 microns[11].

This type of technology is useful in an office setting because it requires the least amount of post-processing. Water jetting takes approximately 5-10 minutes, while the UV light cures the layers as it hardens them, eliminating the need for post-curing. However, the recycling of the support resin may pose an environmental problem. Desktop printer models start at $25,000.

Selective Laser Sintering (SLS)
SLS directs a powerful laser, typically CO_2, at a thin layer of powdered medium (particle size 50 μm, layer thickness between 0.1-0.3 mm) that is spread on a flat bed. The interaction of the laser and powder raises the temperature above the glass transition point, causing adjacent particles to flow together. The pattern of laser application is precisely controlled by the computer-aided design (CAD). The bed is then lowered by a miniscule amount and the next layer of powder is deposited via a roller mechanism on the previous layer and the cycle repeats[7]. Unbounded powder supports the structure as it is being built, and most of this powder is then recycled, reducing post-processing time. However, the surface finish is not as smooth as in stereolithography or other liquid-based technologies.

This type of printing is particularly important in the consumer-electronics, aerospace, and auto industries for its ability to directly produce complex plastic, and metal and alloy components[1]. However, SLS requires a more complex setup than many other printers. The entire fabrication chamber must be sealed and kept at a temperature just below the melting point of the powder, so that the laser need only increase the temperature by a slight amount. Also, the possibility of an explosion when handling large quantities of powder must be neutralized by maintaining the fabrication chamber in an atmosphere of inert gas (typically nitrogen or argon). The final product must be cooled before being removed from the printing chamber, which can take as long as two days for very large or intricate objects[7,15].

Cell Printing
Cell printers use inkjet technology, replacing ink with “bioink,” which is composed of pre-prepared cell aggregates suspended in culture media. A second printer nozzle is equipped to extrude agarose rods, a gel-like substance that serves as a support system to allow cells to grow in the proper shape. Layer by layer, a computer model directs the deposition of the agarose rods and the cell aggregate onto “biopaper,” typically a collagen gel which will disintegrate after a few weeks. If cell aggregates are placed within close apposition in a 3D matrix, they fuse to form a complete disc or tube of tissue[16].

So far, scientists have been successful in using this method to produce functional blood vessels and even nerve grafts. The ultimate goal is to print a working organ, which would require the preparation of several different types of bioinks, a printer with several different nozzle heads and cartridges, each pertaining to a specific cell type, and an incredibly detailed CAD model of the organ. Although this technology is far off, Dr. Anthony Atala has recently succeeded in printing the first kidney[17].

Organ printing has certain advantages over the traditional approach to tissue regeneration: it is an automated pathway that allows for scalable, reproducible, mass production of tissue engineered products; it allows for precise simultaneous 3D positioning of several cell types; it enables creation of tissue with a high level of cell density; it can solve the problem of vascularization in thick tissue constructs; and finally, organ printing can be done *in situ*[16].

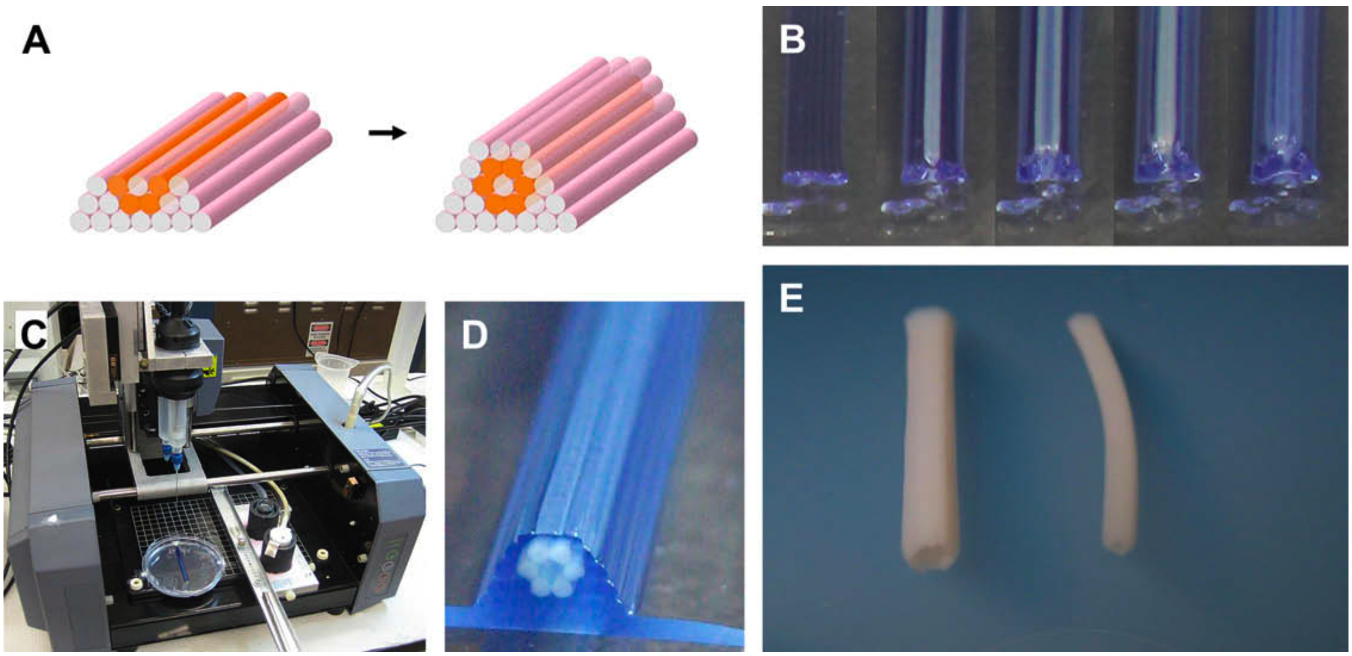

Figure 5. Bioprinting tubular structures with cellular cylinders. (A) Design template. (B) Layer-by-layer deposition of agarose cylinders (stained here in blue for better visualization) and multicellular pig smooth muscle cell (SMC) cylinders. (C) The bioprinter, outfitted with two vertically moving print heads. (D) The printed construct. (E) Engineered pig SMC tubes of distinct diameters resulted after 3 days of post-printed fusion. From REF 16.

Creating the 3D Model

Software & CAD

The CAD model is the first step in the 3D printing process, and arguably the most complex. Typically the model is a polygonal mesh, or a series of triangles oriented in space, that encloses a real volume. The designer must specify such dimensions as the thickness of the walls and the properties of movable parts (i.e. the spring constant of a spring)[10]. The model must be ready to exist in real life before it is exported. 3D design files are then saved, usually in the STL format, and sent to the printer.

The costs of industrial software can range from $5,000 to $15,000, but a growing number of these programs are becoming available for free, such as Google SketchUp[1]. Some companies are also introducing open source designing websites, where anyone can download or upload these CAD files for free. This trend is becoming increasingly popular as the number of at-home 3DP users increase.

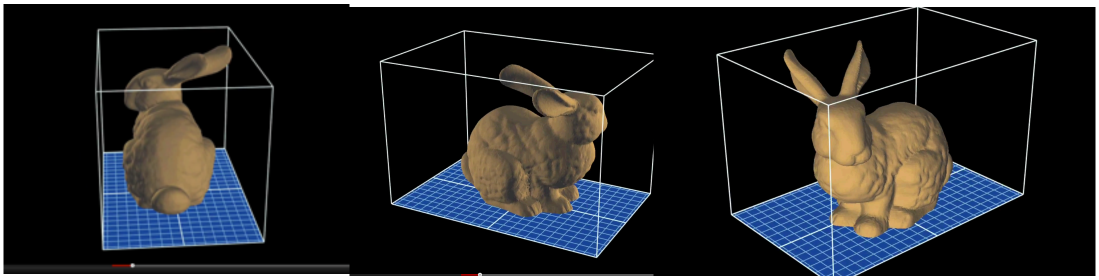

Figure 6. Representations of a three-dimensional CAD model. Adapted from Thingiverse, From REF 4.

3D Scanning

Scanners present an alternative to the CAD model that may be more useful in certain fields, particularly restoration work in art and architecture, replacing broken parts, or for at-home use. There are two main types of scanning technology: laser triangulation and time-of-flight scanners. The former method uses either a laser line or a single line to scan across an object. A sensor picks up the laser light that is reflected off the object, and using trigonometric triangulation, the system calculates the distance from the object to the scanner. These types of scanners are typically short-range and portable[19].

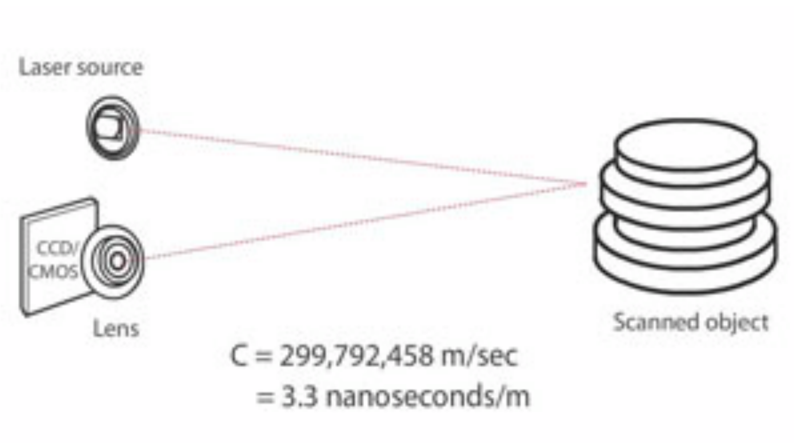

Figure 7. Diagram of a time-of-flight scanner. The speed of light (C) is given above. Using this value, along with precise measurements of time, it is possible to calculate the dimensions of the scanned object. From REF 19.

The second type of technology, time-of-flight scanners, are based on a simple concept: the speed of light is known very precisely, so if we know how long a laser takes to reach an object and reflect back to a sensor, then we know how far away that object is. The time is measured to the picosecond for high accuracy. By rotating the laser and sensor (usually via a mirror), the scanner can scan up to a full 360 degrees around itself. These work in medium- to long-ranges but are typically less portable[19].

However the data points are captured, the end result is the same: thousands of data points about the object's dimensions (and in some models, its colors) are converted by accompanying software into a complete three-dimensional CAD model. This schematic is then sent to a 3D printer.

Future Applications of the 3D printer

3D printing has the potential to transform incredibly diverse industries. Aviation engineers, for example, seek to print airplane wings and eventually a whole airplane. Because printing technology only places material where necessary, printed parts can weigh as little as 60% of their traditionally manufactured counterparts, a huge reduction in an industry where the loss of 1kg can save $3,000 in fuel per year as well as cut carbon dioxide emissions[3]. The company Contour Crafting seeks to use a mega-scale 3D printer to print entire houses, using cement and sandstone as the raw material[20]. At the other end of the spectrum, artists at the Louvre have been using 3D scanning to construct images of precious sculptures and create accurate replicas, while jewelry makers are taking advantage of the technology's ability to create complex intertwined structures[21]. 3D printing is also affecting our healthcare industry: dentists are envisioning a future of customizable dental implants made on demand, while physical therapists praise the creation of individualized prosthetics. In the future, doctors even hope to be able to print new skin directly on patients who have suffered from bad burns, while others are pioneering ways to print soft tissue organs and even bone[17]. An 83-year-old woman in Belgium has recently undergone a successful titanium jaw implant, which was made using a 3D printer[22]. The unique pull of 3DP is that it has almost universal appeal: if you can name an industry, it can most likely benefit from 3D printing.

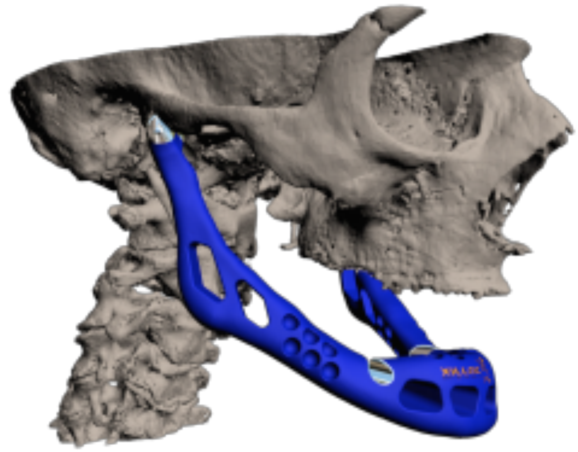

Figure 8. A model of the titanium jaw which was used in jaw replacement surgery. From REF 22.

However, 3D printing will not remain exclusively in the purview of scientists and engineers. Companies like MakerBot, who have created an inexpensive desktop model for at-home use, are seeking to broaden the audience of the printer. Lisa Harouni, founder of Digital Forming, envisions a future in which companies sell CAD models to users over the Internet, who can then download the model, modify it according to their preferences, and then print it from their homes[2].

3D printers represent more than just an innovative way to create things. They may also change the very landscape of manufacturing, possibly even eliminating the need for assembly lines and mass-production, which has been the dominating feature of all economies since the introduction of the factory. Companies will also focus more on the demands of the individual, since every consumer will theoretically have the chance to modify products to their exact specifications. Environmentally, 3DP may also reduce our carbon footprint, since companies may sell digital CAD models rather than shipping an actual product. A potential environmental hazard, however, could result from the increased creation of various photopolymers and solvents.

Of course, 3D printing will also pose some significant challenges, the most noteworthy being pirating. It may become harder to preserve intellectual property, particularly of CAD files that may have taken hundreds of hours to create but which can be stolen in a fraction of that time. Thus, three-dimensional printing, like many other emerging technologies, will still require years before it is introduced to the general public, or before it can safely bring about the changes described above. When it does appear, though, it will undoubtedly revolutionize our industries and our lifestyles.

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