3D PRINTING AND THE FUTURE OF MANUFACTURING
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In this ongoing series of reports about technology directions, the LEF looks at the role of innovation in the marketplace both now and in the years to come. By studying technology’s current realities and anticipating its future shape, these reports provide organizations with the necessary balance between tactical decision-making and strategic planning.

COVER: The Urbee from KOR EcoLogic is the world’s first 3D-printed car. The entire car body is 3D-printed using Stratasys printers, and there are plans to 3D print the car’s interior. The car is designed to be highly energy efficient, including manufacturing processes, and could be in low-volume production by 2014. www.urbee.net
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Who would have thought that modern manufacturing could be done without a factory? Since the Industrial Revolution, manufacturing has been synonymous with factories, machine tools, production lines and economies of scale. So it is startling to think about manufacturing without tooling, assembly lines or supply chains. However, this is exactly what is happening as 3D printing reaches individuals, small businesses and corporate departments.

Today you can make parts, appliances and tools in a wide variety of materials right from your home or workplace. Using a computer, simply create, modify or download a digital 3D model of an object. Click “print,” just as you would for a document, and watch your physical 3D object take shape. No longer the stuff of science fiction, 3D printing is a new reality.

While this new reality is exciting, it also poses significant questions for the future of how we manufacture goods. Factories will not disappear, but the face of the manufacturing industry will change as new entrants, new products and new materials emerge, and mainstay processes like distribution may no longer be needed. Today’s consumers clamor for customized products and services and for speed of delivery. Yet customization and immediacy — right here, right now — are not economical with traditional manufacturing processes, which are optimized for large volumes of consistent output in a factory far away.

3D printing changes the calculus of manufacturing by optimizing for batches of one. 3D printers are being used to economically create custom, improved and sometimes even impossible-to-manufacture products right where they will be used. A single printer can produce a vast range of products, sometimes already assembled. It’s a factory without a factory floor and it has created a platform for innovation, enabling manufacturing to flourish in uncommon areas and spawning a new generation of do-it-yourself (DIY) manufacturers. The new players, with their innovative processes and technology, will disrupt manufacturing as we know it. The Economist calls 3D printing the third Industrial Revolution, following mechanization in the 19th century and assembly-line mass production in the 20th century.¹

3D printing is a classic disruptive technology according to the disruption pattern identified by Harvard Business School professor Clayton Christensen.² It is simpler, cheaper, smaller and more convenient to use than traditional manufacturing technology. Current 3D printing technology is “good enough” to serve markets that previously had no manufacturing capability at all (e.g., small businesses, hospitals, schools, DIYers). However, the technology is not expected to flourish in traditional manufacturing markets for a number of years, so it is unlikely that an entire commercial passenger airplane will be 3D-printed any time soon. Still, traditional manufacturers need to take notice; there are many examples of “good enough” technologies that eventually disrupted and dominated their industry, including transistor radios and personal computers.

All disruptive technologies start out inferior to the dominant technology of the time. When the first experimental 3D printers emerged 20 years ago, they were nowhere near the production quality of traditional manufacturing processes. However, as Christensen observed in his research, the new technologies find a market that is underserved by the current technology (which is often focused on the higher end of the market). 3D printing found rapid prototyping, which was an extremely costly
and labor-intensive process using traditional manufacturing techniques. 3D printing enabled cheap, high-quality, one-off prototypes that sped product development.

As 3D printing technology evolved, it started to be used to directly manufacture niche or custom goods in low volumes. According to Christensen, a disruptive technology continues to evolve to the point where it can serve the needs of the higher-end market at a lower cost, at which point it takes over the dominant players.

This is the path 3D printing is on today. 3D printing is evolving rapidly, with practical examples in numerous industries including defense, aerospace, automotive and healthcare. Although 3D printing has been applied mainly to low-volume production, the products can be far superior (lighter, stronger, customized, already assembled) and cheaper than if created with traditional manufacturing processes. That is because 3D printing can control exactly how materials are deposited (built up), making it possible to create structures that cannot be produced using conventional means.

Another disruptive element of 3D printing is the fact that a single machine can create vastly different products. Compare this to traditional manufacturing methods, where the production line must be customized and tailored if the product line is changed, requiring expensive investment in tooling and long factory down-time. It is not hard to imagine a future factory that can manufacture tea cups, automotive components and bespoke medical products all in the same facility via rows of 3D printers.

Flexibility to build a wide range of products, coupled with the fact that 3D printing can be done near the point of consumption, implies a serious change to supply chains and business models. Many steps in the supply chain can potentially be eliminated, including distribution, warehousing and retail.

The economics of manufacturing also change. Manufacturing is less labor intensive, uses less material, produces less waste, and can use new materials that are light and strong. Depending on the material used, products made with 3D printing techniques can be up to 65 percent lighter but just as strong as traditionally manufactured products. Customization becomes very easy, triggering new product strategies and customer relationships through collaboration with customers to create products (“co-creation”).

It is easy to dismiss the impact of 3D printing if you focus only on the capabilities of today’s 3D printers compared to the capabilities of modern, highly automated factories. Today, and for the near future, 3D printing cannot produce entirely finished products on an industrial scale. However, to dismiss 3D printing’s impact is to ignore the impending disruption, just like the minicomputer makers did when personal computers appeared.

That said, like the personal computer, the first transistor radios and other disruptive technologies, 3D printing will take time to evolve and challenge the incumbents. Today’s technical barriers such as materials cost, quality, size limitations and throughput capacity will need to be overcome. As well, business and economic barriers such as retooling an entire industry and redesigning business strategies, processes and roles will need to be addressed. (See Figure 1.)

Initially, then, 3D printing will focus on new rather than established markets. There are already many examples of this, such as prosthetic limb coverings and vintage replacement parts. Over time, opportunities to complement existing manufacturing will emerge. This may be through leaner methods, hybrid machines, or changes to the supply chain or design process.

As the history of disruptive technologies has shown, 3D printing will not be stopped. Competition will drive the market forward, and over time barriers will come down. History has also shown that once a disruption starts, adoption occurs much faster than anyone imagines possible.
FIGURE 1. 3D PRINTING AT A GLANCE

**UNIQUE ADVANTAGES**
- Affordable customization
- Allows manufacture of more efficient designs — lighter, stronger, less assembly required
- One machine, unlimited product lines
- Very small objects (nano)
- Efficient use of raw materials (less waste)
- Pay by weight — complexity is free
- Batches of one, created on demand
- Print at point of assembly/consumption
- Manufacturing accessible to all — lower entry barriers
- New supply chain and retail opportunities

**AREAS OF FURTHER DEVELOPMENT**
- Printing large volumes economically
- Expanding the range of printable materials
- Reducing the cost of printable materials
- Using multiple materials in the same printer, including those for printing electronics
- Printing very large objects
- Improving durability and quality

Source: CSC

3D printing is providing a platform for collaboration that is accelerating innovation and disruption in the material world, just as the Internet fostered collaboration, innovation and disruption in the digital world.

In *Makers: The New Industrial Revolution*, Chris Anderson, author and editor in chief of Wired, writes: “The idea of a ‘factory’ is, in a word, changing. Just as the Web democratized innovation in bits, a new class of ‘rapid prototyping’ technologies, from 3-D printers to laser cutters, is democratizing innovation in atoms. You think the last two decades were amazing? Just wait.”

This report focuses on the opportunities and potential of 3D printing. Traditional markets may not yet recognize or require the benefits of 3D printing, but that is expected to change as the manufacturing sector feels the impact of this radically different production method.
While experiments occurred as far back as the 1960s, it was not until the mid 1980s when pioneers such as Charles Hull (founder of 3D Systems) and Scott Crump (founder of Stratasys) developed a range of technologies now known as 3D printing. Their work was based on additive processes that created solid objects layer by layer.

As the processes evolved, they became known as additive manufacturing (AM). Because many AM methods were based on ink-jet printing technology, the term “3D printing” (while sometimes misleading) has been broadly adopted by the industry and mass media to refer to any AM process. For simplicity this report uses the term “3D printing” to describe the creation of physical objects, layer by layer, from data delivered to a 3D printer. (See Figure 2).

The difference between traditional manufacturing and 3D printing is how the objects are formed. Traditional manufacturing processes generally use a subtractive approach that includes a combination of grinding, forging, bending, molding, cutting, welding, gluing and assembling. Take the production of a seemingly simple object such as an adjustable wrench. Production involves forging components, grinding, milling and assembling. Some of the raw material is wasted along the way, and vast quantities of energy are expended in heating and reheating the metal. Specialist tools and machines, optimized to produce wrenches of one size and nothing else, are required. Almost all everyday objects are created in a similar (but usually even more complex) manner.

By contrast, a 3D printer can produce an adjustable wrench in a single operation, layer by layer. The wrench comes out of the printer fully assembled, including all its moving parts. (See Figure 3.) After some post-production work such as cleaning and baking, depending on the material, the wrench is ready for use (though currently it is not as strong as its drop-forged metal counterpart).

**Figure 2.** 3D printing, also known as additive manufacturing, builds objects layer by layer. Traditional manufacturing typically uses a subtractive process, whereby materials are cut, ground or molded to create an object.

*Source: Stratasys*

**Figure 3.** This 3D-printed adjustable wrench does not require assembly.

*Source: CSC*
Admittedly, 3D printing isn’t going to take over the creation of wrenches — at least not any time soon. The industry is in its infancy and the technology rarely supports volumes larger than 1,000 units. However, as the technology evolves, volumes will increase.

In the meantime, for low volumes, 3D printing already provides significant value. Development cost and time can be cut by eliminating the need for tooling used in traditional manufacturing. Because 3D printing enables precise control of the material being used, the designer can recreate the internal structure of a product for optimal effect. For example, creating a lattice or honeycomb interior instead of a solid block lightens the product without sacrificing strength. Being able to 3D print the internal structure is a key feature.

There is also reduced waste compared to some traditional manufacturing processes, which can leave up to 90 percent of the raw material on the factory floor. Thogus Products, a custom plastic injection molder, found that for a particular specialty part, 3D printing (the Fused Deposition Modeling or FDM method) reduced the cost of manufacturing from $10,000 to $600, the build time from 4 weeks to 24 hours, and the weight of the object by 70-90 percent. (See Figure 4.)

Furthermore, as the wrench example shows, objects can be printed with a high degree of spatial control. This allows movable components and intricate internal structures to be created in a single print. However, more significantly, the added control frees designers from the limits of traditional manufacturing, allowing people to create and optimize objects that cannot be built with traditional processes. This is opening the door to creativity, including beautiful works of art such as Geoff Mann’s “Attracted to Light,” a piece that traces a moth’s erratic flight around a light source. Such an object is simply not possible using a traditional manufacturing technique.

CHOCOLATE, CELLS, CONCRETE: EXTRAORDINARY PROPERTIES FROM ORDINARY AND NOT-SO-ORDINARY MATERIALS

3D printing started with plastics, but today there is an astounding and growing range of printable materials that includes ceramics, food, glass and even human tissue.

Commercially available machines print in a range of plastics or metals. These printers generally work in one of two ways: a material (e.g., various plastics) is melted and extruded through a tiny nozzle onto the build area, where the material solidifies and builds the object up layer by layer; or a bed of powdered material (e.g., plastic, various metals) is laid down, layer by layer, and selectively fused solid. Usually some post-production work is required, such as cleaning the excess powder, baking to achieve strength or hardness, or dissolving support structures in a solution.

Researchers, organizations and hobbyists have modified the underlying methods to dramatically broaden the range of possibilities. For example, researchers at the University of Exeter modified a 3D printer to print chocolate. (See Figure 5.) Cornell University, working with the French Culinary Institute in New York, took the idea further by creating a range of 3D-printed food items such as miniature space shuttles made of ground scallops and cheese.

The principles have even been applied to biological substances, opening the door to research on a range of health applications:

- Washington State University has developed a bone-like material that provides support for new bone to grow.
- Researchers from the University of Glasgow have developed a system that creates organic compounds and inorganic clusters, which they believe could have long-term potential for creating customized medicines.
- Organovo has created a range of human tissue using human cells as material and has even printed a human vein.
Most fascinating is research that shows how 3D printing can revolutionize the properties of products. Just like laminated wood (plywood) has long been used as a lighter, stronger and more flexible alternative to solid timber, 3D-printed components can exhibit properties that exceed the capabilities of traditionally manufactured components, even if they are made from the same material. Two examples of this are 3D-printed wood that does not warp, and the work underway to use living cells to 3D print organs needed for transplants. (More on that later.)

Researchers are working on a range of techniques that can control the exact material properties of printed components, even down to the microscopic crystalline structures of metals, essentially changing how the material’s underlying atoms and molecules are arranged. For example, 3D printing of metal can result in more uniform microstructures due to rapid solidification, in contrast to the traditional metal casting and forging that require metal to cool from the outer surface to the core. This allows engineers to control the object’s strength, hardness, springiness, flexibility and ability to support stress. The result of this research will be products exhibiting combinations of physical, electrical and mechanical properties that are only dreamed about today.

The University of Illinois Lewis Research Group has created a number of custom “inks” (printing materials) with extremely small feature sizes. (See Figure 6.) The researchers have demonstrated many functional materials for improved conductivity, lighter-weight structures, and even self-healing polymers. For example, the team has created a reactive silver ink for...
high-performance electronics that is faster to make (minutes to mix versus hours using particle-based inks) and can be printed in small amounts. The ink can be stored longer than traditional ink and has a lower processing temperature, allowing electronics to be printed on low-cost materials such as flexible plastic, paper or fabric substrates. In another application, the silver ink has been printed onto three-dimensional surfaces to create small electrical antennas that perform an order-of-magnitude better than traditional antenna designs. These antennas show potential for implantable or wearable antennas, sensors and electronics.

Also conducting research into 3D printing and materials is the MIT Media Lab, which is experimenting with printing large molds for concrete structures using a spray polyurethane foam. (See Figure 7.) Printing with polyurethane offers benefits in weight, cure time, control and stability compared to concrete. It also serves as thermal insulation. Once printed, the mold can be filled with concrete or another castable building material. MIT has printed several prototype wall molds that are 5-6 feet tall as it explores the benefits of large-scale 3D-printed molds including design, cost, efficiency and safety.

Contour Crafting proposes 3D printing an entire house, targeting low-cost and emergency housing (after a natural disaster, for example). The company claims an entire 2,500-square-foot home can be built in 20 hours (doors and windows added later) with extremely large 3D printers and specially formulated concrete. The social implications of using automated construction to replace dilapidated or destroyed dwellings are significant.

Still, the price of materials is a significant barrier to 3D printing. For example, the cost of plastic feed material used in 3D printing ranges from $60-$425/kilogram (2.2 pounds), while the equivalent amount of material used in traditional injection molding is only $2.40-$3.30. Although the higher cost is not a problem for prototyping or small volumes, it is not economical for large volumes.

For some materials, 3D printing is more than just a niche alternative — it is actually the ideal production method. Titanium is one example; it is light, stronger than steel (for its density) and more corrosion resistant than stainless steel. In fact, it is a near-perfect metal for many applications. Aside from its current cost, the main drawback of titanium (and the reason its use is limited to specialist applications in aerospace, medical implants, jewelry and performance cars) is that it is difficult to work with. It has a tendency to harden during cutting, which results in high tool wear, and when being welded it is susceptible to contamination that weakens the welds if the proper precautions are not adhered to strictly.

This is where 3D printing comes in. Directly printing in titanium is attractive because it eliminates the problems of machining. Further, as the printing machines get bigger, entire assemblies can be printed, eliminating the need for welding.

To address the current high cost of titanium metal (it is as much as 50 times more expensive than steel), researchers are developing processes to create powdered titanium at much lower costs. Currently the printing powders are produced by reducing titanium ingots into fine, uniform powders (in a highly energy-intensive process). But just as the Bayer process reduced the cost of aluminum from $1,200/kilogram to $0.60/kilogram at the end of the 19th century, today's research is looking at industrial processes for producing titanium printing powders at a fraction of the current cost.

**FIGURE 7.** MIT is experimenting with 3D printing large forms made from polyurethane (like the one seen in this rendering). The forms would be filled with concrete and used in building construction.

*Source: Mediated Matter Group, MIT Media Lab*
Prototyping new products is the largest commercial application for 3D printing today, estimated to be 70 percent of the 3D printing market. Prototyping gives designers (and their customers) a way to touch and test products as concepts or functional objects early in the design cycle. This avoids expensive changes later in the process, saving significant time and money when bringing new products to market.

By rapidly printing prototypes, manufacturers can significantly shorten the development lifecycle. One example comes from Akaishi, a Japanese manufacturer of corrective footwear and massage devices. The company found that by 3D printing prototypes in-house, it could reduce lead time of new products by 90 percent compared to its previously outsourced prototyping service. This allows its designers to have 100 percent confidence in a product’s functionality before it ever reaches the customer. Prototyping also facilitates experimentation and innovation. For example, using 3D printing, Bell Helicopter can test new designs in days versus weeks using traditional methods.

In some industries, 3D printing has shifted from prototypes to direct part production, also known as direct digital manufacturing. The technology is being applied to short production runs and does not require tooling, thus allowing flexibility, adaptability and speed to market. This is enabling countries with strong intellectual capital but high manufacturing costs to once again compete in manufacturing. As Scott Hay, founder of 3De, a small rapid product development company based in Florida, told IndustryWeek, 3D printing “is a terrific win for American manufacturing.” 3De designs specialized high-precision surgical systems, which are then printed by a U.S.-based 3D printing service, GPI. There is no cost advantage in off-shoring the production of 3D components, unlike traditional manufactured components that are cheaper to manufacture overseas.

Today 3D printing is being used in many areas for both prototyping and direct digital manufacturing. Following are examples from defense, aerospace, automotive and healthcare.

**DEFENSE**

Components used in military equipment must be strong, durable and, above all, reliable, as failure can put lives at risk. Consider the mount for camera gun sights on the M1 Abrams tank and Bradley fighting vehicles. These high-precision components are mounted on the external body of the tanks, where they must survive incredibly harsh shock, vibration and environmental conditions. EOIR Technology, a leading defense system design and development company, was able to manufacture mounts durable enough for use on the tanks using a 3D printer. What’s more, by switching to 3D printing technology, the company reduced the manufacturing costs from over $100,000 per unit to under $40,000.

In the future, it may be possible for the military to print replacement parts on the battlefield instead of relying on limited spares or the supply chain. While this is still some time away, there are developments that suggest movement in the right direction. For example, the Trainer Development Flight (TDF) facility at Sheppard Air Force Base in Texas is using 3D printing to develop training aids for the
Air Force and other U.S. Department of Defense branches.\(^{27}\) Given the highly specialized nature of the equipment, such as unmanned aerial vehicles (UAVs), and the low volumes required, using original parts or even manufacturing replicas is a lengthy and expensive exercise. However, using 3D printing in combination with traditional manufacturing techniques has enabled the government to save over $3.8 million from 2004-2009, not to mention provide improved and timely training in areas including avionics, weapons systems, medical readiness and telecommunications systems. More recently, student interns working on a U.S. Army research project created and flew a 6.5-foot-wingspan plane (a UAV) made entirely of 3D-printed parts to help study the feasibility of using such planes.\(^{28}\)

Another benefit is the use of distributed manufacturing to address supply chain issues. Components mass-produced in one part of the world can take weeks to arrive at an assembly factory. But 3D printing components on site eliminates shipping time, reduces friction in the supply chain and reduces inventory levels at the factory.\(^{29}\) The 3D mapping was critical for its visualization and speed; one can imagine it being applied in other fields that require knowing the lay of the land, from mining to archeology.

**AEROSPACE**

Like many industries, aerospace is leveraging 3D printing to improve the performance of assets, reducing maintenance requirements, consolidating components and saving fuel costs with lighter parts.

Boeing, a pioneer in 3D printing, has printed 22,000 components that are used in a variety of aircraft.\(^{30}\) For example, Boeing has used 3D printing to produce environmental control ducting (ECD) for its new 787 aircraft. With traditional techniques, the ECD is created from up to 20 parts due to its complex internal structure. However, with 3D printing, Boeing produces the ECD as one piece. The new component reduces inventory, does not require assembly and improves inspection and maintenance times.\(^{31}\) As the 3D-printed parts weigh less, the aircraft’s operating weight decreases, resulting in fuel savings. According to American Airlines, for every pound of weight removed from its aircraft, the company saves more than 11,000 gallons of fuel annually.\(^{32}\) Boeing, as well as other aerospace giants GE and the European Aeronautic Defence and Space group (EADS), maker of the Airbus, are conducting further research to optimize parts such as wing brackets. (See Figure 8.) Ferra Engineering, an Australian aerospace contractor (that supplies Boeing and Airbus), has a contract to 3D print large two-meter-long titanium parts for the F-35 joint strike fighter, reducing machining time and materials waste.\(^{33}\) Boeing even envisions 3D printing an entire airplane wing in the future.\(^{34}\)

![Figure 8. This 3D-printed metal Airbus wing bracket is lighter and stronger than the conventional wing bracket in the background that it could potentially replace.](source:EADS)
or even on Mars. That is exactly what groups like Made in Space and Lunar Buildings are investigating. Both organizations are developing tools, processes and systems for directly manufacturing in space, avoiding the costly and decade-long planning cycles required to send a rocket into space with the necessary replacement parts and tools. Made in Space has a contract with NASA and is currently conducting zero gravity tests, with plans to trial 3D printing on the International Space Station. This would allow astronauts to print tools and parts in space exactly when needed.35 (See Figure 9.)

Today, NASA’s next space exploration vehicle (rover) includes about 70 3D-printed parts; NASA engineers also 3D print prototypes to test parts before production.36

Looking ahead, NASA is exploring 3D printing as a service (3DPaaS) for rapid pre-prototype work. “We are bullish on 3D printing,” says Tom Soderstrom, IT chief technology officer at NASA Jet Propulsion Laboratory. “3D printing makes it easier to capture the imagination of the mission concepts. We can see what others are imagining.” Engineers could use 3DPaaS to rapidly obtain peer reviews, additional design concepts and approval to prototype. Initial prototyping and iterations would be done using low-cost, fast-turnaround open source CAD tools and 3D printers. “We like the open source, open design approach. It would allow us to get outside ideas about the designs more easily and to get started much sooner,” Soderstrom adds.

Once the design is deemed ready for full-scale prototyping, it would go to large-scale 3D printers to build a version 1.0 object. The result would be faster build times, lower costs and more confidence in the version 1.0 design.

Space is not the only extreme environment for 3D printing. Industrial designer Markus Kayser has demonstrated a solar-powered 3D printer creating crude glass out of sand in the Sahara desert.37 (See Figure 10.) It isn’t space, but it does show that 3D printing can be done with basic resources in extremely remote environments.

**AUTOMOTIVE**

For years, major automotive manufacturers have been using 3D printing for prototyping. However, the automotive industry is poised to begin applying the process to more than just prototypes of small custom parts.

Take, for example, the Urbee, billed as the world’s first printed car. The two-passenger Urbee, created by KOR EcoLogic, dismisses preconceptions about limits to 3D printing sizes. To be clear, not all parts are 3D-printed — just the shell of this hybrid prototype car — though interior components are...
The most inspiring use of 3D printing is in the healthcare industry, where 3D printing has the potential to save lives or dramatically improve them. 3D printing in healthcare still has some years to go before mass adoption, but early developments to create tissue, organs, bones and prosthetic devices provide a glimpse of how lives may be improved.

Using a patient’s own cultured cells or stem cells, the Wake Forest Institute for Regenerative Medicine has developed a 3D printing technique for engineering tissue and organs. The ultimate goal is to help solve the shortage of donated organs available for transplant. Scientists are working on a variety of projects including ear, muscle and a long-term effort to print a human kidney. (See Figure 12.) The printer is designed to print organ and tissue structures using data from medical scans, such as CT or MRI. The basic idea is to print living cells — and the biomaterials that hold cells together — into a 3D shape. This organ or tissue structure would then be implanted into the body, where it would continue to develop. The kidney project is based on earlier work that used cells and biomaterials to engineer a “miniature” kidney that was able to produce a urine-like substance when implanted in a steer.

In addition, there are a growing number of applications for 3D printing in surgery. For example, the Walter Reed Army Medical Center has created and successfully implanted...
over 60 titanium cranial plates. In June 2011 the first 3D-printed jaw, also made of titanium, was successfully implanted in an 83-year-old woman by Dr. Jules Poukens of Hasselt University. These implants perfectly match a patient’s body and provide better fixation, which can reduce surgery time and infection.

Perfectly matching a person’s body is key for prosthetic devices too. 3D printing is ideal for these highly customized, small production runs (quantities of one) that demand strong but light-weight materials. 3D printing would enable those with limb loss to get exactly what they want for look, feel, size and weight, all for a fraction of the cost of a traditionally-made prosthetic. Bespoke Innovations, now owned by 3D Systems, uses 3D printing to make custom coverings for artificial limbs and aims to 3D print the entire prosthesis in the future. (See Figure 13.) A related example is 2-year-old Emma, born with a rare disease called arthrogryposis, who wears 3D-printed “magic arms” that give her the strength to lift her real arms — and a whole new lease on life. The “magic arms” can be reprinted as she grows and are light enough for her 25-pound body. Another example are 3D-printed hearing aids that, though pricey, provide excellent sound quality due to their custom fit.

**FIGURE 12.** These 3D–printed structures — kidney (top left), ear (top right) and finger — could one day help address the organ shortage and the need to repair if not replace damaged body parts.

Source: Wake Forest Institute for Regenerative Medicine

**FIGURE 13.** The 3D-printed metal lace cover on this prosthetic leg is delicate yet strong and reflects the wearer’s individuality.

Source: Bespoke Innovations
3D Printing and the Future of Manufacturing

3D printers have created a new generation of DIY manufacturers. These individuals are using 3D printing services online or their own low-cost 3D printers to create custom products that address unmet needs.

**GROWING SERVICES MARKET**

3D printers make it economical to create highly unique products that quench the rising thirst for personalization. Whether it is a smartphone case personalized with your name (see Figure 14), an avatar from World of Warcraft or a self-designed robot toy, there are a range of services like Freshfiber, FigurePrints, My Robot Nation and Sculpteo at one’s disposal. The consumer market is buzzing with affordable custom products, all available through the Internet using “as a service” techniques. Expect to see 3D printing stores in a shopping mall near you soon!

A growing population of DIY designers is using these services to create and upload products and ideas to websites like Shapeways, a start-up “working to democratize creation by making production more accessible, personal, and inspiring.”49 (See Figure 15.)

**LOW-COST PRINTING IN UNEXPECTED PLACES**

In 2008-09 the 3D printing market took a major turn with the availability of open source manufacturing kits priced under $1,000, including various derivatives of the RepRap open source project (discussed later) and the Cupcake CNC from MakerBot Industries. These devices ushered in a new group, hobbyists, who previously couldn’t afford their own personal machines. And like all technologies, prices have continued to fall; for example, the

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**FIGURE 14.** 3D printing services make personalized products like this smartphone case affordable. Source: Sculpteo

**FIGURE 15.** The Shapeways 3D printing marketplace removes barriers to manufacturing by providing 3D printing services via the web and enabling people to share their designs. Source: Shapeways
Printrbot LC launched in 2012 for $549.50. The availability of low-cost 3D printers has spurred many to manufacture at home, bypassing numerous steps. (See Figure 16.)

What’s more, with their roots in open source, many 3D printers are evolving rapidly and can now compete with some commercial printers. (See Figure 17.) For those that need higher quality products, a variety of online printing bureaus allow prints in different materials (metals, plastics and glass).

To get an idea of what these DIY manufacturers are printing, take a look at Thingiverse.com, a website with self-created files for 3D printing. Created by MakerBot Industries, the website has a large community of individuals who have shared over 25,000 models ranging from toys and gadgets to replacement parts. All are available for downloading and printing by anyone. Recently, one of our researchers faced the prospect of a 14-hour flight holding an ebook reader, with no time to buy a reader stand before leaving for the flight. After a few minutes searching on Thingiverse.com, he was able to download a foldable stand design, print it in 45 minutes, and use it on the flight that night. (See Figure 18.)

In addition to homes, low-cost printers have made their way into other unexpected places. For example, at...
Outside of ordinary replacements, there are some parts and objects that are simply no longer in stock. For example, due to the scarcity of replacement dials for a vintage boombox, someone created a printable alternative.\(^5\)

That is the beauty of 3D printing: creating functional, if not obscure, parts. One of the most high-profile examples comes from American comedian Jay Leno. In an article in Popular Mechanics, Leno discusses his use of 3D printing to re-manufacture parts for his rare and vintage vehicle collection: "Any antique car part can be reproduced with these machines — pieces of trim, elaborately etched and even scrolled door handles. If you have an original, you can copy it. Or you can design a replacement on the computer, and the 3D printer makes it for you."\(^6\) He goes on to explain how his 1907 White Steamer is back on the street due to the use of 3D printing to recreate an incredibly rare slide valve (D-valve).

Using 3D printing, Leno can create functional parts for testing (i.e., to see if the part is the right size and shape before using a traditional CNC milling process), create molds to cast a part in aluminum, and even replace metal parts with plastic. He explains: "My EcoJet supercar needed air-conditioning ducts. We used plastic parts we designed, right out of the 3D copier. We didn’t have to make these scoops out of aluminum — plastic is what they use in a real car. And the finished ones look like factory production pieces."\(^7\)

FIGURE 18. This e-reader stand was 3D-printed by our researcher in less than an hour. The design is available on Thingiverse by designer Billy Carr ("uni stand" by codemanusa).

Southview Middle School in Edina, Minnesota, the industrial technology teacher uses a 3D printer so students can experience their designs and concepts as physical models.\(^2\) In Australia, a local municipality has created a 3D printing lab in a library so the community can play with and understand the technology.\(^3\)

It is important to note that libraries, schools and homes have different quality requirements than factories. Consumers, who have never had such manufacturing powers before, are quite forgiving of faults in 3D-printed objects they have created themselves, as long as the object serves its required function. Consumers may not be so forgiving of such flaws in products they purchase.

**MAKING THINGS WORK**

While not for everyone, 3D printers allow the Mr. or Ms. Fix-It to take control of their appliances. Examples of replacement parts emerging in the Thingiverse library include a wheel for a dishwasher, a keyboard support stand and a portable camera battery door. Some of these parts have had significant downloads. For example, a touch screen stylus for the Nintendo DS has over 300 downloads;\(^4\) clearly, a lost stylus is a common problem with a simple solution.

Although it is hard to predict where 3D printing at home will lead, it is a safe bet that consumers won’t use these printers to recreate what they can already buy in stores.

3D printing is breaking down barriers to manufacturing. Although it is hard to predict where 3D printing at home will lead, it is a safe bet that consumers won’t use these printers to recreate what they can already buy in stores. They will be creating things you simply can’t buy, such as irreplaceable parts and personalized objects and gadgets.
3D printing at work or at home signifies the democratization of manufacturing. (The very name “3D printing” instead of “additive manufacturing” is a nod to a broader audience.) Until now, the creation of high-quality physical products or prototypes required very expensive machinery and investments in tooling and sophisticated CAD/CAM software. This posed a barrier, preventing many good ideas from ever being built (even to a prototype stage), as most people lacked the skills and financial resources to design, let alone manufacture or distribute, a product.

However, in the last decade these traditional barriers have been stripped away.

While 3D printing is at the heart of the DIY production process, there have been developments in all elements of the DIY manufacturing lifecycle including free or low-cost 3D modeling and scanning tools (for design), sharing websites (for marketing and distribution), investment websites (for funding), and a new open design ethos (industry collaboration). These elements now allow almost anyone to become a manufacturer or contribute to the manufacturing process.

**SOPHISTICATED MODELING MADE SIMPLE**

3D modeling and visualization play a crucial role in the early phases of product development. However, in the past, software was often expensive and required extremely powerful machines, making personal use impractical. Today this has changed. Now, most home PCs can run some of the world’s most sophisticated software such as Creo 2.0 or SolidWorks. What’s more, there are a number of free or low-cost modeling tools, such as 3DTin, SketchUp and Blender, that contain powerful design capabilities but are simple enough for anyone to use. For something even simpler, there is Tinkercad, which is free and let’s people play with the basics of 3D modeling.

Bypassing the modeling effort altogether, a range of affordable 3D scanners enables physical objects to be digitized, modified (within limits) and reproduced directly by a 3D printer. Interestingly, several software products are blurring the distinction between scanning and modeling. By automating much of the 3D modeling experience, they allow almost anyone to rapidly generate sophisticated models. Check out Continuum Fashion and FaceGen. Both services — one for fashion, the other for facial modeling — hide the back-end 3D modeling effort from the individual, who simply wants the output. More recently, Autodesk launched a cloud service that allows people to create 3D models with a few swipes on their iPad or by uploading photos of an object from multiple angles.

Another example of the democratization of design comes from 3D software house Digital Forming, which provides software that enables companies to share product design with their customers. The software lets consumers tweak dimensions of the desired product, whether it is the perfect lamp or a custom cuff link. Consumers can adjust shape, surface design, color and material (within limits). This closer relationship between consumer and manufacturer will spur a greater expectation for customization.

Although 3D printing makes one think of the hardware and objects produced, a key part of the magic of 3D printing is the software. Formlabs made software ease-of-use a cornerstone of its sophisticated 3D printer (discussed later). Elsewhere, a team of researchers has created software that examines the geometry of the CAD model and determines where to add joints, so elbows and knees get hinges, for example. The software optimizes for full movement and no collisions with other joints or possible movements. 3D printing then allows the whole model, including its joints and moving parts, to be materialized all at once. Sophisticated modeling made simple.
DÉJÀ VU: THE INTELLECTUAL PROPERTY DEBATE

Despite the allure of 3D printing and the democratization of manufacturing, 3D printing poses serious questions about intellectual property. To be clear, this issue is not unique to 3D printing; patent and copyright infringement has been debated for decades, stoked more recently by the advent of Internet piracy, and will continue to be fought for years to come.

Nonetheless, 3D printing and supporting tools allow almost anyone to intentionally or unintentionally recreate an existing product design, distribute that design, and manufacture the product. Although technically this was possible decades ago, today’s digital designs and 3D printers, linked by the Internet, make it significantly easier.

Armed with a low-cost 3D scanner and 3D printer, you can buy a product off the shelf such as a toy, scan that object or its parts, and distribute the design all over the world. Previously, manufacturing posed a barrier because the model could not be created and distributed readily like this; if you wanted that toy, you had to purchase it. However, with 3D printers it is possible to simply print the toy yourself. While the individual benefits, the manufacturer loses out on its significant investment in design, manufacturing and marketing.

Some are fearful that 3D printing will cripple traditional manufacturers, likening it to Internet piracy in the music and movie industries. While those in the music industry argue that illegal downloads have hurt it severely, others believe the industry was already in trouble and needed to reinvent its dated business model. Either way, piracy is a heated issue.

As with music and movies, digital rights management (DRM) discussions for manufacturing designs have begun to appear. Intellectual Ventures, run by former Microsoft CTO Nathan Myhrvold, has been granted a patent for managing “object production rights” for 3D printing specifically (though not exclusively); it remains to be seen to what extent this patented technique for preventing unauthorized object copying will be used.

In his paper “It Will Be Awesome if They Don’t Screw it Up: 3D Printing, Intellectual Property, and the Fight Over the Next Great Disruptive Technology,” Michael Weinberg, a staff attorney at advocacy group Public Knowledge, agrees with concerns but also comprehensively breaks down arguments and current legislative issues across multiple intellectual property dimensions. He highlights both the threats and opportunities of 3D printing. An important reminder from Weinberg is that progress, and those who are inspired, should not be stopped by those who fear.

SHARE THE DESIGN, SHIP THE DESIGN

After producing a product on a 3D printer, creators turn to marketing and distribution. Several years ago, if funding was scarce, the creator would initially manufacture and market a low volume of product for a specialist application. Over time, if the product was successful, further investment would be made so larger volumes could be marketed and distributed around the world. It was only at this point that the product could reach a broader customer base.

Now, thanks to online marketplaces like Thingiverse, Shapeways and Sculpteo, the marketing and distribution problem has been significantly reduced. As of August 2012, Shapeways had nearly 7,000 shops and over 160,000 members who had printed over one million products. Shapeways enables designers to get paid for their products and also handles distribution, so products can be purchased and delivered anywhere in the world.

The Chinese e-commerce giant Alibaba has been a leader for some time in connecting consumers and small businesses to large-scale manufacturers, breaking down barriers to manufacturing. This consumer-to-business model encourages small, custom transactions and is “ideally suited for the micro-entrepreneur of the DIY movement.”

But Alibaba was about shipping products, whereas 3D printing is about shipping designs, continuing the evolution of the digitization of things. Being able to ship and print the design means that printing can be done on demand, whether through a service bureau, a company’s own 3D printing capability or even the end consumer. These innovative printing options will drive the next generation of distribution and pose major upheaval for traditional manufacturers, whose businesses revolve around shipping products, not designs.
THE RepRap STORY — OPEN SOURCE MANUFACTURING

The year 2008 was a turning point for DIY manufacturing because a new product called the RepRap was released. The RepRap is a low-cost 3D printer, but what is truly unique about the RepRap is how it is designed, manufactured and distributed.

In May 2008, the second RepRap printer was assembled. Within minutes of being turned on, it had started printing the components to build the third RepRap, and so on. Today, it is estimated that over 20,000 RepRaps exist, most of them using components manufactured by other RepRaps — a neat example that gets closer to the vision of self-replicating machines.

One of the aims of the RepRap is to enable individuals or small enterprises, especially in poorer parts of the world, to be able to build complex products for themselves with virtually no capital investment (a RepRap kit costs about $500).

Inspired by open source software models, the RepRap design is also open source. This means the entire design (hardware, electronics and software) is not protected by any patents and anyone can modify and contribute improvements (provided they make them freely available). A whole community of enthusiastic users actively participates to innovate and improve the design.

Because the design is freely available, anyone can download, manufacture and sell the RepRap. In this way, many individuals and small companies manufacture and sell RepRaps online, either in kit form or as fully assembled and tested models.

As a result, the rate of innovation of the RepRap and its derivatives is accelerating faster than equivalent commercial 3D printers. In the future, open source approaches may be applied to all sorts of manufactured products, leading to superior products that are more reliable and functional because a global community continually improves them.

CROWD-FUNDING

Although low-cost 3D printers and accessible CAD software lower barriers to entry for bringing new products to market, some capital is still required. This is where pioneering initiatives like Kickstarter come in. Kickstarter, a crowd-funding website for creative projects, allows anyone with a good idea to advertise for seed funding, usually provided by large numbers of small investors. The rewards for the investor are set by the entrepreneur and typically range from thank-you certificates for small donations to free copies of the product being sponsored. Most projects raise less than $10,000 though the highest funding to date for a single project was $10 million.

Formlabs, an MIT Media Lab spin-off, achieved its 30-day funding goal of $100,000 in less than three hours and reached over $1.5 million in one week. What’s all the excitement about? Formlabs provides an affordable high-resolution 3D printer (still in testing) for designers, engineers and serious hobbyists. The Form 1 printer uses stereolithography, the method used in high-end printers, thus bringing professional-quality printing to individuals. The democratization of manufacturing and the democratization of investing go hand-in-hand.

OPEN DESIGN

“Open source” is best known as the term associated with freely-available software like Linux, Android and Apache. The philosophy behind open source is that information should be shared freely by a community of contributors, who work to improve the product and contribute their work back to the community for free use. The power of this philosophy is demonstrated by Wikipedia, which, through the contributions of millions of people, has become the premier reference encyclopedia in dozens of languages and is freely available, while its “closed” competitors (like Encyclopedia Britannica) have become obsolete.

Similarly, the term “open design” has come to be applied to the design of physical products, machines and components through public sharing and contribution. Low-cost 3D printers and availability of software for creating and sharing printable designs are enabling the necessary conditions for sharing designs of physical components. The concept of open design is starting to take off with products like VIA OpenBook (an open source laptop) and RepRap (an open source 3D printer).
As well as fostering small-scale DIY product innovation by interested communities, open design can provide a framework for developing advanced technology projects that are beyond the resources of any single company or even country.

In 2011, the U.S. Defense Advanced Research Projects Agency (DARPA) turned to the public for inspiration to design a replacement for the iconic Humvee. DARPA issued the Experimental Crowd-derived Combat-support Vehicle (XC2V) Design Challenge, conducted in partnership with open design automobile manufacturer Local Motors. In a stunning display of the power and enthusiasm of the open design community, Local Motors turned the winning design into a working prototype in just 14 weeks — about one-fifth the time of the automobile industry average. (See Figure 19.)

**FIGURE 19.** This potential Humvee replacement was created by an open design community, which built a working prototype in just 14 weeks.

*Source: Local Motors*
While it is difficult to say with certainty how 3D printing in its various forms (e.g., desktop, large-scale) will impact traditional manufacturing, emerging trends indicate that a fundamental paradigm shift has already started. As 3D printing evolves, the new world of manufacturing looks like this:

- **Time-to-market for products shrinks.** This will be due, in part, to faster design and prototyping cycles as a result of 3D printing, but also to the elimination of tooling and factory setup times for new products. Being “agile” will no longer be a competitive advantage but a basic necessity to stay in business.

- **Products have superior capabilities.** The barriers for manufacturing will be lowered, bringing new competitors with new ideas. At the same time, products incorporating 3D-printed components will exhibit superior features such as being smaller, lighter, stronger, less mechanically complex and easier to maintain. These products will hold distinct competitive advantage.

- **Open design is here to stay.** Communities of end users will increasingly be responsible for product designs, which will be available to anyone with the necessary skills and tools who wants to design and then manufacture. These open-design products will be superior to proprietary products. Manufacturers will compete on how well they implement the designs and their build quality, which will be mercilessly rated by end users on the Internet.

- **Customization is the new normal.** As innovative companies use 3D printing and other rapid techniques to offer customization at no additional cost, consumers will come to expect customization as the norm. The per-unit manufacturing costs of small production runs (even batches of one) will approach those of long runs as technology barriers fall.

- **The economics of off-shore change.** The price advantage associated with mass production in low-cost regions will be challenged by 3D printers providing just-in-time manufacturing near the point of sale or point of assembly. Supply chains will be re-optimized to factor in the advantages of just-in-time, particularly for low-volume or highly specialized components. Conversely, designers will be able to minimize costs by using low-cost, high-volume components wherever possible, connected with specialized just-in-time components produced at the point of assembly.

Amidst this new world of manufacturing, traditional manufacturing processes must evolve or die. (See sidebar.) In a recent report, LEF researcher Simon Wardley noted that when an activity, in this case manufacturing, becomes a commodity, traditional practices must evolve to embrace the new, though highly disruptive, business processes. He states that the 3D printing disruption “will almost certainly be led by new entrants whose practices will be radically different from those of existing players.”70 Therefore, in preparing for this change, traditional manufacturers must keep abreast of evolving 3D printing practices and be aware of their own internal barriers (e.g., culture, organization) that could prevent them from taking advantage of the change.

As more organizations and individuals become manufacturers, the lines between manufacturer and customer will blur.
HYPOThETICAL CASE STUDY:
3D PRINTING BLURS RETAIL AND MANUFACTURING

Gordon Fuller, CSC

Retro Company is a specialty retailer selling reproduction home furnishings (door handles, cabinet pulls, lanterns) in mall stores and online. The company is evaluating a five-year strategic plan to open 200 additional stores. To support the demand from those stores, U.S.-based Retro is considering expanding production at its two factories in North America and increasing its sourcing from Asia. However, the company also realizes that its product line may be compatible with 3D printing, a potential game-changer for its business, so it incorporates the technology into its planning.

After analyzing the materials needed for its products, expected use and durability, and future printing capabilities, Retro determines that 3D printing is possible, not only by Retro but by its customers. The company dives further into analysis for the following questions:

- Since much of its inventory is reproductions of American colonial and other historic objects, does Retro own the intellectual property of these designs and can the company protect it?
- If customers print the products themselves, can the company offer any warranty or guarantee?
- Is the company liable for safety issues when it does not control manufacturing?

The results of this analysis persuade Retro that intellectual property protection cannot be enforced since Retro itself takes photographs of historical artifacts for its reproductions. This makes the company vulnerable to alternate designs from competitors or home enthusiasts. Legal input suggests that Retro can alter its warranty and return policies depending on the source of the product, but the company does alert its lobbyist in Washington, D.C. to monitor legislation regarding at-home manufacturing.

Although the costs of manufacturing, inventory and distribution are expected to fall dramatically over the next few years by using 3D printing, the unknown impact on sales when customers print designs themselves means a cost-benefit analysis is impossible at this early stage. The company does estimate, however, that 60 percent of its customers will have the capability to print their own products after eight years.

Build or Buy?

Retro turns to finding ways to improve sales and customer retention to respond to this at-home manufacturing market. The company analyzes its store and website demographics to determine customer profiles and to identify customization opportunities 3D printing would offer for both customers and product designers. It also segments customers into “build” or “buy” categories. A complete redesign of the website would be required since the company would be selling 3D printer files along with manufactured items. The website would need to offer choices of material, identify compatible printers based on the materials, and provide other options. This new sales channel would also require additional services and opportunities to enhance customer loyalty.

As the impact of customer choice becomes evident to more divisions within the company, enforcement of intellectual property protection is again fiercely debated as a way to retain market share. Hosting a design store for enthusiasts and possible competitors may cannibalize sales even more. Retro concludes that more customers would be alienated by restrictions than would be retained by rights management and reaffirms its strategy to remain open with its designs and website.

Retro’s manufacturing strategy is also revised. With the drop in physical goods sold as people purchase digital designs, production volumes are projected to decrease. The company determines that additional sourcing is still needed from Asia, but decides to reduce the length of its fixed-term contract from eight to four years and instead purchase options for years five through seven. However, Retro realizes its suppliers are vulnerable to 3D printing as well, and due diligence is required on the customer mix of those companies; if too many of its suppliers’ other customers are impacted by 3D print-
ing, then the supplier could collapse, leaving Retro without inventory.

This ties into the calculations for the planned 200 retail stores. Focus groups suggest that customers would still patronize a showroom to handle the merchandise, especially if any item from the catalog could be printed on site as a sample. New break-even numbers are estimated for retail operations, and supplier vulnerability is offset by contingency plans to add more printers to stores if needed.

**Digital Inventory**

The dramatic shift in sales volume from retail operations to an online design catalog will be a surprise to shareholders, and the temptation is to squeeze profit from the existing stores before the paradigm has shifted. Retro is also wary about signaling its intentions to the market and losing a competitive advantage. The company’s board determines that its fiduciary responsibility to shareholders outweighs preserving the status quo. It approves confidential plans to convert the company’s entire inventory into 3D printer files, as well as ensure that all new product designs are created as 3D files from the beginning. Work begins on the website redesign as well as a pilot store program for the new retail sales concepts. Store expansion plans move ahead, though the planned locations for the first two years are reduced until the preliminary analysis from the pilot program is ready.

Retro knows it is breaking new ground in the 3D printing arena, but wants to do so ahead of competitors or new entrants. The retailer is seeing the lines between manufacturing and retail blur as customers take on manufacturing themselves and retailers sell digital designs, not physical products. As Retro expects its entire business model to shift in response, one strategic option being considered is whether a new company should be formed as a “pure” 3D enterprise. Retro decides not to do this for the first two years, preferring to evaluate its strategy and personnel to determine if they are sufficiently agile to make the switch.
Like all technology, 3D printing will continue to evolve. In addition to cost reductions (particularly in the consumer space) and eventual miniaturization, researchers are breaking new ground in terms of print size, material integration and speed. There are even systems being developed that combine the benefits of the traditional subtractive processes (e.g., CNC machining) with 3D printing (additive processes). These hybrid approaches perform 3D printing and machining at the same time, eliminating post-processing. For example, most metallic objects created by 3D printing require human intervention for either finish-machining or polishing. However, a Japanese heavy machinery manufacturing company, Matsuura Machinery Corporation, has developed a system that combines 3D printing (laser sintering technology) with high-speed milling that mills edges of the printed object in five-layer increments.71

These developments are creating new, unimagined solutions to existing problems, opening the door to new market entrants and paving the way for a constant stream of “world’s firsts.”

Researchers at the Vienna University of Technology have created 3D objects only microns in size using a technique called two-photon lithography.72 The researchers’ breakthrough has been to speed the technique, making it more feasible for industry. Whereas printing speeds used to be measured in millimeters per second, they are now measured in meters per second. The race car in Figure 20, approximately 285 microns long (the average human hair is 40-120 microns in diameter), has 100 layers that were printed in four minutes.73 While the structure is already miniscule, it is expected that printers will one day produce even smaller objects, opening new possibilities for innovation in areas such as medicine.

Breakthroughs in multi-material printing are enabling more complex products. The current leading multi-material 3D printer is the Objet Connex500, which allows up to 14 plastic-like materials to be printed at the same time. This could be a rubber-like plastic or a more rigid ABS plastic. What is amazing is that the materials are all printed in one job run. Instead of being printed as separate components and attached one at a time, they are fused together simultaneously.74 Multi-material printing lets creators combine various properties in one model. One day a complete product or device could be printed as one, such as a mobile phone that includes plastic cover, metal, electronics and glass screen.

Although such a Star Trek-type replicator is still years from being mainstream, another device that is similar to the replicator for its recycling capabilities may be closer to reality. The Filabot is a desktop device that can recycle a range of plastics, including milk jugs and soda bottles, into spools of plastic filament for 3D printers.75 (See Figure 21.) Funded and launched through Kickstarter, the Filabot has moved from concept to prototype in a matter of months and contains some 3D-printed parts itself.76
It is clear that traditional industry players will compete with new entrants offering alternative solutions previously not possible, thus disrupting markets. Consider Align Technology, which in 1999 introduced clear teeth aligners under the Invisalign brand that compete directly with wire dental braces. Costing slightly more than braces, the aligners incrementally shift teeth until they are straight, without the discomfort or look of wire braces. The aligners are made with 3D printers, enabling the mass customization necessary to create cost-effective customized dental devices. In the past, creating such high-quality molds of individual mouths had not been economically feasible. This early use of 3D printing enabled an industry first — invisible orthodontics — and injected competition into an otherwise staid market.

Expect to see a number of other industry firsts over the next few years. They will join a list that includes:

- the first fully printed shoe, created by a Dutch research institute, TNO Science and Industry, and concept design firm Sjors Bergmans Concept Design

- the first printed bike, made from nylon and as strong as its steel and aluminum counterpart, developed by the European Aerospace and Defence group (see Figure 22)

- the first artificial insect with 3D-printed wings that has sustained untethered hovering flight for 85 seconds, by researchers at Cornell University (see Figure 23)

**FIGURE 21.** The Filabot lets people recycle plastic in a desktop environment to create their own plastic filament for a 3D printer. The Filabot extends the DIY of 3D printing to the raw materials themselves.

*Source: Tyler McNaney
*Photo credit: Whitney Trudo

**FIGURE 22.** The first 3D-printed bike, made from nylon and developed by the European Aerospace and Defence group, is strong enough to replace its steel and aluminum counterpart. The bike is a technology demonstrator that lays the groundwork for bike manufacturers to one day be able to 3D print a bike to fit the rider’s exact size.

*Source: EADS

**FIGURE 23.** Researchers at Cornell University created the first artificial insect with 3D-printed wings that sustained untethered hovering.

*Source: Charles Richter and Hod Lipson*
Given the deep roots of traditional manufacturing and the challenges the nascent 3D printing movement poses, will 3D printing really disrupt the manufacturing industry? In short: yes. As The Economist reported, we may be on the verge of the third Industrial Revolution, and like all revolutions, the impacts run wide and deep. (See Figure 24.) The question for manufacturers anywhere in the supply chain is how they will need to change — not disappear — to adapt to 3D printing.

In the short term 3D printing will not go head-to-head with traditional large-scale manufacturing but will increasingly be used for prototyping, tooling of traditionally manufactured items, and the direct manufacture of highly custom or technically complex low-volume items.

As the limits on object size and printing speed decrease and the price of printing materials falls, the economics of manufacturing will change dramatically in favor of 3D

### FIGURE 24. 3D PRINTING IMPACTS

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Source: CSC
printing. This is especially the case when considering the end-to-end cost of designing, manufacturing, assembling, transporting, distributing and operating a product. People will increasingly use products that contain 3D-printed components (or are entirely 3D printed), from cars and airplanes to consumer electronic devices and kitchen appliances.

Because of the superior characteristics of 3D-printed products, these products will be more desirable. Start-up manufacturers will flourish with new and innovative ideas, and they will have the means to rapidly scale up production with minimal capital investment. These start-ups, with their agility and incredibly short time-to-market, will be the competitors of tomorrow.

Anyone doubting the new sources of competition need only look at the capability of the hobbyists and open design community today. Without access to large factories, teams of industrial designers or big capital, communities can profitably sell 3D printers for as little as $600 and build prototype military vehicles in 14 weeks. These guys are already beating large-scale corporations hands-down in niche areas.

For large-scale corporations that design and build things, 3D printing is an opportunity for IT to forge new relationships with manufacturing and with those who need to visualize designs, like scientists and engineers. One example of this is part of a broader strategy by James Rinaldi, CIO of NASA Jet Propulsion Laboratory, to “change what ‘IT’ stood for from ‘information technology’ to ‘innovate together.’”

Gabriel Rangel, solutions engineer in JPL’s Office of the CIO, innovated together with the fabrication group at JPL to create its 3DPaaS model. The key innovation is the consumerization of 3D printing, which lets many innovations flourish by using desktop 3D printing in-house for pre-prototyping. Later, the printing of fewer, more expensive, more refined 3D designs can be automatically outsourced as a service. The result is that by partnering with scientists, engineers and the shop floor to re-think processes — aided by new design tools and 3D printers — the IT group has accelerated JPL’s ability to print physical designs early in the product development cycle that can be shared, modified and re-printed, over and over, long before a prototype is built. This, in turn, means higher confidence in the final design that is prototyped and, ultimately, produced.

3D printing is a digital technology, not just a manufacturing technology. With its open and democratic properties, 3D printing sets the stage for innovation.

For large-scale corporations that design and build things, 3D printing is an opportunity for IT to forge new relationships with manufacturing and with those who need to visualize designs, like scientists and engineers.

3D printing is a digital technology, not just a manufacturing technology. With its open and democratic properties, 3D printing sets the stage for innovation. It has lowered the barrier to entry for manufacturing, igniting the creativity of the masses. 3D printing is creating new products and services, supporting greater levels of collaboration, and fostering disruptive market entrants.

Manufacturers need to prepare for these disruptions and can begin by asking some key questions that challenge current assumptions. (See sidebar.)
QUESTIONS FOR MANUFACTURING FIRMS

To help manufacturing firms grasp the future opportunities and challenges of 3D printing, here are 10 questions to consider. Some may have already been answered and some may be uncomfortable or difficult to answer, but all are relevant.

1. When products can be manufactured with the same ease as walking down the hall to print paper copies, how will you keep your company’s business model relevant?

2. What are the business implications of delivering a digital design rather than a physical product to your customers? When your customers do manufacturing instead of you, what are the implications for product quality, product safety (e.g., a product recall) and intellectual property protection?

3. How can your company use 3D printing to improve your end product? Possibilities include consolidating components to reduce maintenance, creating lightweight products and leveraging new materials research.

4. In a world of 3D printing, will your customers continue to need large production runs? Even if it is more cost-effective for your company to manufacture large quantities, will your customers demand more frequent changes and upgrades? Has the expected lifetime of your product changed?

5. Is your factory going to become an assembler rather than a manufacturer? A hybrid? What effect will this have on your existing production lines for length, direction, workstations, staffing, storage, etc.? How will your inbound logistics processes change to reflect those alterations?

6. What is the new relationship between IT and manufacturing? Between IT and product designers, scientists and engineers? How can IT use 3D printing to enable manufacturing, not overtake it?

7. Where are the opportunities for driving greater customer intimacy, such as customization and co-creation with your end customer?

8. How will you prepare for new competitors, including new entrants and DIYers? Do the current benefits of 3D printing (low cost, high customization, delivery close to point of use) challenge your existing product line? Do future areas of 3D printing research pose a threat?

9. What organizational factors could prevent (or support) your adoption of 3D printing — for example, operating model, resource allocation, on-shore/off-shore mix, financial model, culture — and how will you address them?

10. Where should your company make capital investments today? What training and education investments are required? What investments should your company avoid?

The changes surrounding 3D printing are significant; we are only scratching the surface of what the ultimate impact will be. The glimpses of disruption seen today suggest wholesale change in the future. Customized, no-ship manufacturing will one day be as common as desktop printing. When that happens, and factories without factory floors are the norm, it will be hard to imagine how companies and consumers once lived without 3D printing.
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APPENDIX: FURTHER READING

For those interested in keeping up with the latest developments in the 3D printing world, the following provide great reading.

- 3D Printer: http://www.3dprinter.net/author/mark
- 3D Printer Blogs: http://3dprinterblogs.com/
- 3D Printing News and Trends (Howard Smith, CSC): http://3dprintingreviews.blogspot.com
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- It’s a 3D World: http://blog.objet.com/
- Singularity Hub: http://singularityhub.com/
- Makers: The New Industrial Revolution, by Chris Anderson
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Vivek Srinivasan (left) and Jarrod Bassan (right) conducted the research for 3D Printing. This work has furthered their understanding of the potential opportunities of this new technology and how it can be leveraged across industries.

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Jarrod is a senior consultant specializing in the mining and metals industry. He works with tier-one global companies to develop innovative business and technology solutions that directly improve the productivity, efficiency and safety of their operations. Jarrod recognizes the potential for 3D printing to one day solve the supply and logistics problems related to maintaining complex mining equipment in extremely remote locations. He has an interest in robotics and has previously competed in international competitions with a team of autonomous soccer-playing robots, which in part spurred his interest in 3D printing. jbassan@csc.com

Combining their passion for the application of emerging technologies and their experience in the mining industry, Vivek and Jarrod have co-authored past works such as The Augmented Mine Worker — Applications of Augmented Reality in Mining and A day in the life of a mine worker in 2025 for the Australasian Institute of Mining and Metallurgy. Vivek and Jarrod are based in Melbourne, Australia.

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