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Disruptions, decisions, and destinations: Enter the age of 3-D printing and additive manufacturing

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Abstract Until recently, most manufacturing processes have been 'subtractive' in that matter is removed (e.g., scraped, dissolved, turned, machined) from a substance in order to produce the desired product. 3-D printing turns traditional manufacturing on its head in that it uses an 'additive' process. Similar to laser and inkjet printers, 3-D (three-dimensional) printers produce pieces by depositing, or adding, layers of material—plastic, polymer filaments, metals, and even foodstuffs—until the desired product is realized. This means that the creation and production of 'one-offs' is not only easy, it is also economically viable. 3-D printers are becoming ever more affordable, and it is not hard to envision them being as common in most homes in the near future as their two-dimensional counterparts are today. This article presents a 3-D printing primer for non-technical managers. It then considers the profound impact that 3-D printing will have on firms of all kinds as well as on individual consumers. In addition, it raises the substantial questions that 3-D printing will pose to policy makers from both intellectual property and ethical standpoints.

1. An invention that could remake the world

Before May 2013, 3-D printing had not been a topic of many conversations, at least not outside the circles of committed technophiles who had already hailed it as the future—or the end—of manufacturing. Low public awareness changed when the first 3-D printed gun was announced and the code for its production was shared online by Cody Wilson, a 25-year-old law student at the University of Texas. The so-called 'Liberator' is still the world's most notorious 3-D printed object to date. The news that anyone could buy a relatively inexpensive 3-D printer—Wilson bought his on eBay—and produce a functioning gun at home made 3-D printing a very hot topic. Discussion revolved around personal liberties and the "right to print arms," gun control, homeland security (whether the plastic gun could be detected by airport

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scanners), and whether sharing the design online was ethical, let alone legal (S. Brown, 2013).

While the 3-D printed gun got the world's attention, it also added confusion to public awareness of the 3-D printing process and the constructive opportunities it presents. Our aim in this article is to alert executives to the potential of 3-D printing: to confront them with the decisions that will need to be made, the disruptions they will face, and the destinations 3-D printing will take them to in the future. We proceed as follows: First, we provide a brief user-friendly introduction to the phenomenon of 3-D printing, describing what it is, how it works, and what it can do. We also discuss the pros and cons of 3-D printing and address what it will mean to firms and consumers. Next, we consider the substantial legal implications that 3-D printing will have, with particular reference to intellectual property. We conclude by speculating how 3-D printing will evolve in the future and how it might alter the manufacturing, marketing, and strategic landscapes.

2. 3-D printing: If you can draw it, you can print it

For most technologies, the first working versions are usually bulky, expensive, and slow. They initially remain largely in the lab, unknown to the general public. When these technologies become more affordable and user-friendly, they enter the market as supposedly new inventions. 3-D printing is no exception. It has stayed under the public radar since 1983, when design engineer Charles "Chuck" Hull was frustrated by the long wait time and expense of having new injection molded parts produced. Even after design and blueprints were completed and the mold was made by a toolmaker, it would be weeks—if not months—until the part was delivered (Hessman, 2013). Hull's 'stereolithography' overcame these problems and allowed rapid casting of metal parts for large manufacturers such as automotive companies.

Hull's process, which forms the basis of 3-D printing today, differs from traditional production processes in one fundamental way: it is not subtractive. Traditionally, most production techniques create three-dimensional products through 'subtractive manufacturing,' whereby undesirable or superfluous material is removed to arrive at the desired artifact. This is an age-old process. For example, a totem is carved by removing pieces of timber from the trunk of a cedar tree, and a wooden lamp stand is produced by using a lathe to cut superfluous wood to arrive at the desired shape. Most artifacts today are still produced at least in part by means of subtractive machining techniques such as grinding, cutting, drilling, filing, turning, or milling. Even non-machined products are fabricated in a similar fashion; for instance, maple syrup is made by boiling off water from the sap until the desired sugar concentration is reached. Subtraction is everywhere, and that's why 3-D printing as an additive process is so revolutionary.

'Additive manufacturing,' as the name suggests, builds products from the bottom up, just as children of all ages construct complex artifacts by combining simple Lego blocks. Additive manufacturing is a little more complex, but can be thought of as a computer-controlled hot glue gun that uses a carefully calculated and measured combination of basic elements that bond together as they are laid down, by adding each layer to the previous (Berman, 2012; H. J. Brown, 2012). With the 3-D printing mantra, "if you can draw it, you can print it," any computer generated 3-D model can be produced. With a 3-D printer in-house, the substantial improvements in prototype production speed for which Hull yearned 30 years ago can be achieved today at a fraction of the cost. Indeed, it is this combination of flexibility, speed, and low cost that makes this technology so disruptive.

Nowadays, a variety of 3-D printers—some as small as a desktop paper printer—are available to anyone. They range in price from $300 for the cheapest option, to mid-range models between $500—$2,000, and about $3,000 for high-end versions. Industrial 3-D printers and those that can use advanced materials, however, are much more expensive. Basic 3-D printers are no longer only available in specialty stores: They can be purchased at regular electronics retailers such as Amazon, Office Depot, and Wal-Mart. There are even downloadable open-source instructions on how one can build a 3-D printer at home.

Admittedly, the use of the term 'printing' adds to the confusion that surrounds the 3-D phenomenon. The etymology of the term suggests that printing is about making an impression or a mark—for example, by a stamp, a seal, a printing press, or a computer-controlled printer. In these 2-D contexts, similar techniques and materials were used. Typewriters used ribbons, ink-jet printers used cartridges, and laser printers require toner to print texts, images, or photographs onto paper, plastic, and textiles. Additive 3-D printing, on the other hand, uses filaments (i.e., input materials) to print all sorts of products. Contrary to public belief, and possibly fueled by the Liberator, 3-D printing is not just about producing products from plastic—although BS and PLA plastics are the cheapest raw materials for 3-D printing. Various raw materials can be used by different 3-D printing methods, including polymers, epoxy resins, nylon, wax, powders, oils, and nutrients, as well as titanium, sterling silver, stainless steel, leather, sandstone, and materials that mimic human cells.

But how exactly does one print three-dimensional products made out of any of these or other materials? 3-D printing follows the sequential stages of design, printing, and post production, each of which offers the user a number of alternatives.

2.1. Design

Users can create new 3-D designs by means of a wide range of computer aided design (CAD) or animation modeling programs, ranging from free or fremium options like Google SketchUp, 3-DTin, or TinkerCAD to relatively expensive but also more advanced programs like AutoCAD or Pro/Engineer. 3-D printers can print with accuracy down to 16 micrometers, which is smaller than the finest human hair. Most printers still produce single-colored objects, but this does not mean that all designs necessarily need to be monochrome. Depending on the printing process, the filament can be changed to change colors for some multicolored objects, or so-called 'dual extruders' can be used to print two-colored objects.

Alternatively, users can 3-D scan existing products with simple but relatively inaccurate scanners for mobile phones and tablets (e.g., 123-D Catch) or with larger and more powerful 3-D scanners. Once a product is scanned, it can be manipulated using the 3-D design programs mentioned above. Unsurprisingly, a number of online storefronts like MakerBot's Thingiverse, Shapeways, or Ponoko have emerged via which users can download—either for free or for a fee—the designs for all sorts of products. Once the design stage is completed, its blueprint is exported in the 3-D printer-readable SLG (for stereolithography) file extension.

2.2. Printing

Once the design is completed, the printer will convert it into individual 2-D layers. Its print head then passes over a building platform to add, or lay down, layers of the material, one at a time, to make the 3-D object—hence additive manufacturing. Three methods are available for the different types of raw materials (physics.org, 2014).

The first method, the original Stereolithography (SLA), uses light—usually from an ultraviolet laser—to turn chemical resins like liquid plastics into solids. The second method, known as Fused Filament Fabrication (FFF), does not require a light source: its molten ink simply becomes solid when it emerges from the printer head, similar to how chocolate or cheese solidifies when it cools down. Both methods build layer upon layer until the final product is finished. The third method, called Selective Laser Sintering (SLS), fuses layers of powdered material such as stainless steel powder. After the powder is preheated in the powder bed, the 3-D printer's laser raises the powder temperature of the desired regions to its melting point to create and join the layers of the desired 3-D object.

Currently, many of these processes can be completed on 3-D printers at home, but that does not mean that users have to own one. Printing metals, for instance, requires capital-intensive 3-D printers that are not feasible investments for the lay user. One printing alternative is to upload the design to printing sites like Shapeways or Kraftwurx, which print and ship 3-D objects much like online photo printing services. Another option is to consult the online service MakeXYZ to find neighbors who will share their 3-D printers for free or for a nominal fee.

2.3. Post production

Today, the overall shape and mechanical fit of printed objects seems to be the primary goal of 3-D printing. The surface treatment is often secondary. However, for many products, such elements matter, and "like builders of dollhouses and model trains" (Griffin, 2014), many 3-D printers are busy deburring, sanding, polishing, sealing, and painting their new objects. Some require post-production soldering and friction-welding of separately 3-D printed parts to create the final object. A 3-D printed metal door handle, for instance, could be polished, painted, or gold-plated so that it is not just functional, but also aesthetically pleasing.

2.4. Sharing

Of course, while there is no need to make one's 3-D printed project successes or failures publicly available, the small but rapidly growing community of early adopters strongly supports a sharing mentality across a number of social media choices (Kietzmann, Hermkens, McCarthy, & Silvestre, 2011). Users share their progress on forums, offer videos of their progress on video-sharing sites, and upload their designs to the abovementioned 3-D content sharing sites where they can be sold or shared freely.

3. Disruptions: What 3-D printing can mean to firms and consumers

The original mother of invention for 3-D printing was Hull's necessity for quicker prototyping. Today, the speed and convenience of rapid prototyping allows firms, small and large, to be more nimble and to produce different versions of a product overnight, test them, and produce improved versions without delay. This not only improves the production process, but also has a profound impact on how creative inventors can be in their product development. A rejected part or a dud no longer costs a lot of money or time, but can become a creative part of experimentation and research and development. However, there are lots of other advantages for firms.

From an *inventory management* perspective, for example, firms can save space and cost by on-demand replication of stock items with a 3-D printer rather than keeping items stockpiled in anticipation of a future need. Some examples are obvious, others less so. For instance, under the Space Technology Mission Directorate, NASA is already building some of its prototypes of tools and instrument parts for current or future missions using 3-D printing (Lipson & Kurman, 2013), and is supporting a study on 3-D printing of food in space (NASA, 2013). The same is true for instructions for vaccines, which could be distributed and 3-D printed quickly in case of a contagious virus outbreak—like the pandemic H1N1—or more generally sent to areas in need throughout the world (Hernandez, 2012). For all other industries, too, 3-D printing can become the new *kanban*, a true just-in-time inventory management solution.

From an industry *supply chain* perspective, consider product warranties, component upgrades, repairs, and recalls. What if firms enabled the downloading of 3-D printing instructions closer to the point of purchase or consumption, eliminating users' need to order and wait? Twenty years ago, if a manual for a kitchen appliance was lost, a printed replacement manual had to be ordered and delivered. Today, people simply download the pdf from a website. Tomorrow, with 3-D printing, they will effectively download not only repair instructions, but also the parts needed. For most industries, such a change from traditional supply chain to distributed manufacturing will be very disruptive; for instance, 3-D printing is bad news for parts suppliers that capitalize on distributing highly marked-up replacement items. However, despite many projections, there could be good news in 3-D printing for manufacturers. If manufacturers started thinking and acting more like service providers (Vargo & Lusch, 2004) and made their parts downloadable, they would not only capture the market of parts suppliers, but also help speed up the abovementioned repair or replacement process for their customers. An appropriate revenue model for downloadable parts, 3-D instructions—much like all digital goods without a considerable cost of production—could yield an attractive return on investment. What's more, without such a service, customers might simply reverse-engineer parts they need and share their instructions online. Manufacturers would lose control over the specifications of the instructions and the quality of the objects to be printed.

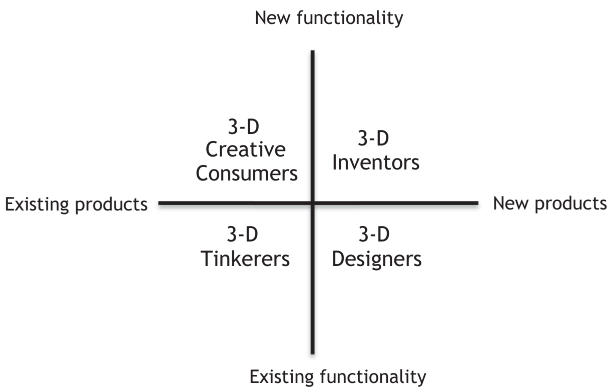
Of course, 3-D printing also presents enormous opportunities for tailor-made, *custom products* to be produced. Some will be high-end, like implants or prosthetics such as Handie, a 3-D printed hand that uses sensors to read brain impulses in order to control movement. With the help of a smart phone, Handie computes the electrical impulses on the skin's surface to grab objects of different shapes. The product Cortex addresses more common problems. After a traditional X-ray and a 3-D scan of a limb, a 3-D cast that provides lightweight, ergonomic, waterproof, and ventilated support for the treatment of bone fractures can be printed.

3-D printing also promises to reduce the *ecological footprint* of today's manufacturing systems and their reliance on physical distribution channels. The positive impact of printing objects closer to the point of consumption, thereby reducing road and air miles, can be a substantial contribution to solving today's intensifying pollution problems. To ensure that the cure is not worse than the illness and that 3-D printing does not create more waste (remember the promise of computers and the 'paperless office'?) through the numerous, rapidly developed objects that end up in landfills around the world, new industries aimed at collecting 3-D printed objects and recycling them into new filaments will emerge.

Aside from firms, the advantages for consumers are attracting more and more people to 3-D printing. Two dimensions seem to separate different types of consumer-driven 3-D printing projects: the degree to which they work on existing or new products, and the degree to which their printed objects improve or sustain the functionality of the original product experience. When combined, these two dimensions suggest that four different types of consumers will be active in 3-D printing (Figure 1).

Many consumers will be drawn to 3-D printing's possibilities for working on existing offerings. ***3-D tinkerers*** will help maintain existing products by developing 3-D printed objects for replacement or repair (e.g., parts for a home appliance). On the other hand, *3-D creative consumers* (see, for example, Berthon, Pitt, McCarthy, & Kates, 2007) are motivated by the possibilities of adapting, modifying, or transforming existing proprietary products to improve the associated experiences; for example, a 3-D creative consumer developed a converter brick to connect the Duplo bricks from Lego and Brio

Figure 1. Consumer 3-D printing



wooden train tracks. *3-D designers* are driven by creating altogether new products that, by and large, do not create new functional experiences but focus on remodeling the form-factor of existing ones. As hobbyists, they may only design coat hooks, doorstops, and backscratchers for fun, but those that are more serious design—among other things—jewelry and fashion items. *3-D inventors* who think outside the box will invent new 3-D printed products and introduce new functionalities and new experiences. For example, the aforementioned Handie prosthetic hand and the Cortex cast for fractures were among the top three submissions to the 2013 James Dyson Award for world-changing ideas.

All these types of consumer 3-D printing will require a lot of filaments for their projects. Similar to the history of 2-D printing, 3-D printer hardware has already become more affordable, but through the razor-blade revenue model (Teece, 2010), the expensive ink makes printing intrinsically costly. To alleviate this problem, 3-D inventors have developed products that extrude and reclaim High Density Polyethylene: in other words, machines that 'reduce, reuse, recycle' not only bad 3-D prints, but also old plastic milk or shampoo bottles to allow users to make their own 3-D printer plastic while saving money (3-D Printing for Beginners.com, 2014).

4. Decisions: Thorny ethical and legal 3-D printing issues

Despite its obvious promise, 3-D printing will raise many thorny legal issues for firms and ethical issues for policy makers. Just as the Internet brought the retail storefront onto the consumer's computer screen, 3-D has the potential to bring the factory into the consumer's living room.

From a firm perspective, few managers raised in a pro-producer climate have the consumer instincts required to compete on customization (D'Aveni, 2013). Firms will need to re-examine their stances toward the consumer creativity enabled by 3-D printing (Berthon et al., 2007): Will they encourage and enable consumer creativity, will they actively resist and repress it, or will they simply ignore it? The intellectual property issues experienced by the producers of digital content, such as music and film, will now come to the physical world. While fake goods have long been a problem, they have still typically relied on large manufacturing facilities, mostly in the developing world. Now, rather than purchase the real thing or a knockoff, a consumer can scan a friend's original and print his or her own—and then make the scan available on the Internet so that anyone can simply download the scan and print unlimited numbers of the object.

From a policy perspective, the general prognosis that creative consumers will make their own things presents thorny issues, not just to manufacturers, but also to legislators and policy makers. The question of standards is a case in point: How will we deal with standards, or rather, the potential threats that a lack of standardization brings? If we can print objects, who tests the instructions for quality assurance and the objects for quality control? There might be a new generation of viruses waiting, not only for the equipment, but also possibly for people. Bio 3-D printing of drugs and vaccines at a high level, or even the simpler printing of foods—despite their enormous positive potential—might have scary implications. Dishonest individuals are already selling fake drugs for medical treatments; they might soon be selling manufacturing instructions for fake drugs or for illegal recreational drugs online.

5. Destinations: The future of 3-D printing

Trends alone suggest that 3-D printing is going to be a very big deal. The sale of products and services worldwide is expected to grow to $3.7 billion in 2015, and by 2019, the industry is forecasted to be worth over $6 billion. In terms of hardware, prices will come down, printer features will continue to improve, and 3-D prints will become more sophisticated.

At the same time, the field is moving rapidly from the printing of relatively simple 3-D objects to applications in complex fields such as food and health. 3-D printed meat promises to satisfy the human need for protein while simultaneously having a far less detrimental impact on the environment than poultry, pork, and beef production (Fox, 2012). In addition, medical professionals have used 3-D printing to create hearing aids, custom leg braces, and even a titanium jaw. In 2013, a team of researchers, engineers, and dentists created the world's first prosthetic beak for a wounded bald eagle (Li, 2012). 3-D printing ranges from very large (e.g., the firm WinSun makes a 3-D printer large enough to print entire houses), to small (dental technicians are beginning to print tooth crowns and implants), to ultra-small. For instance, geneticist Craig Venter, of human genome fame, is working on biological structures—such as vaccines—that can be created in digital form, emailed to wherever they are needed, and produced using local 3-D printing technology (Kuneinen, 2012).

Naturally, the number of different types of 3-D printing consumers—currently four—will continue to grow. To the next generation, which has already started experimenting with 3-D printers in high school media clubs, 3-D printing will be a normal part of everyday life. More and more 3-D tinkerers will print parts, 3-D creative consumers will improve existing offerings, 3-D designers will develop innovative shapes and fashions, and 3-D inventors will introduce altogether new functional experiences and 3-D printed products.

Of course, the resulting printing instructions will be co-produced and shared online, with or without the permission of organizations whose products are affected. The controversial Swedish file-sharing website Pirate Bay has already begun to offer a new category of downloads called 'physibles'—data files that deliver real, physical objects to anyone with a 3-D printer—believing that the "future of sharing is about physible data" (Moscaritolo, 2012).

Comfortable managers might argue that much of this is in the distant future. For example, according to Gartner, 3-D bioprinting, 3-D scanning, and consumer 3-D printing in every home are still 5 to 10 years out. However, Gartner also pointed out that enterprise 3-D printing is already on the "slope of enlightenment" on the Gartner Hype Cycle (Gartner, Inc., 2013)—a forecasting tool that is being used in academia as well (e.g., Lapide, 2011; O'Leary, 2008)—and only 2—5 years away from the "plateau of productivity." While these timelines might seem long to the average user, organizational strategies need to consider the next 5 years at minimum. As with most disruptive technologies, it is likely that we will overestimate the potential of 3-D printing in the short term while underestimating it in the long term. In this article, we have outlined the basics of 3-D printing for managers as well as some of the decisions they will need to consider. We have noted disruptions that the technology might cause and what these mean to firms and consumers. In addition, we highlighted legal and ethical issues that the technology has in store for policy makers. While we have begun to speculate on the directions the technology will take in the future, astute managers in almost every industry will want to keep a closer eye on 3-D printing technology as it continues to evolve.

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