

Managing the Disruptive Effects of 3D Printing

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Abstract

As an effective alternative to mass production, 3D printing is capable of economically producing small quantities in local markets, making goods to order based on customer preferences, and generating little waste. 3D printing also has the potential to disrupt the Chinese economy as its manufacturing is based on economies of scale and the use of low-skilled workers. The ability of 3D printing to integrate many components into one product has major implications for supply chain relationships. This paper contrasts 3D printing with traditional manufacturing and mass customization. It explores the disruptive effects of 3D printing and examines key managerial issues in implementing 3D printing. Strategies to compete against 3D competitors (niche-based products, mass customization, inventory-based strategies, and outsourcing) are discussed.

3D Printing: A Disruptive Technological Innovation

In contrast to traditional manufacturing that creates products using molds or removing material via cutting, lathing, or grinding, 3D printing (also called additive manufacturing or rapid prototyping) creates three-dimensional objects by adding layers. There are three major 3D printing technologies: selective laser sintering (SLS), fused deposition modeling (FDM), and stereolithography (SLA). Each technology uses a different process to build the layers that results in a final product. SLS melts powdered feed material into a desired object by adding a new layer of powder as prior layers are cooled and solidified. In FDM hardened feed material (usually plastic on a coil) is fed into a 3D printer and then melted layer-by-layer to produce the desired object. FDM is the most widely adopted and consumer-friendly 3D printing technology. SLA uses a moving laser beam to build the

Managing the Disruptive Effects of 3D Printing

object, layer-by-layer, from a liquid polymer that hardens on contact with the laser's ultraviolet light.¹

The potential impact of each of these technologies on traditional manufacturing processes and supply chains is very similar. SLS, FDM, and SLA can economically produce small quantities in local markets, make goods to order based on customer preferences, and generate little waste. Each technology also enables firms to separate responsibility for product design and production.

This paper contrasts 3D printing with traditional manufacturing and mass customization. It explores the disruptive effects of 3D printing and examines key managerial issues in implementing 3D printing. Strategies to compete against 3D competitors (niche-based products, mass customization, inventory-based strategies and outsourcing 3D design and production) are discussed. Other considerations in planning and implementing 3D printing include reexamining a firm's current supply chain network, quality assurance programs, and intellectual property strategies.

The potential impact of 3D printing on mass production has been compared with such disruptive technologies as digital books and music downloads. As with digital books and music downloads, 3D printing disrupts the current supply chain by drastically reducing unsold finished goods inventory, producing customized products at low cost, and transmitting product design specifications via downloads.

Several studies of the future of 3D printing examined its potential for high growth, to become an effective alternative to mass production, and to be a major disruptive innovation. One study viewed 3D printing as the beginning of a new era, with major implications for the adoption of technology and business models that companies can use.² A study by the European Commission found that over the past decade 3D printing has transformed the way in which products are designed, developed, and distributed. The range in opportunities available as a result of 3D printing span from product design and development, customization, and restructuring of the supply chain for greater efficiencies.³

Two important technological developments will have a major positive impact on the adoption of 3D printing. The first enables different materials to be used in a single 3D print run. This expands the number of potential 3D printing applications. A second development is the availability of 3D printers that are up to 40 times faster than those released five years ago. The faster speed reduces the number of printers required and enables 3D printers to have larger print runs.

Despite the major significance of 3D printing, with rare exceptions, there has been no academic research on its social and economic implications.⁴

Most of the academic literature on 3D printing has focused on engineering, material science, and computer science.⁵ This paper aims to fill the managerial-focused gap.

The Potential Disruptive Impact of 3D Printing

One study identified three major characteristics of a disruptive innovation: (1) the innovation enables a user to accomplish a new task that was impossible before the innovation was invented, (2) the innovation generates new markets, and (3) the innovation uses less costly materials or more efficient technologies.⁶ Another study found that disruptive innovations succeed by targeting overlooked market segments through delivering more suitable functionality at a lower price.⁷ In contrast to a minor innovation based on small improvements of existing products, a disruptive innovation represents a radical change as well as a significant improvement and/or customer experience.⁸

The disruptive nature of 3D printing can be seen by looking at its impact on a firm's current supply chain, its role in developing a new value proposition among consumers (based on delivery speed and customization), the ability of small firms to successfully challenge large established firms, and the use of new business models by new competitors.⁹

One study suggests that the emergence of 3D printing will affect the pattern of global production and introduce a new era of customization, where global production will become more localized.¹⁰ Another study found that 50 percent of the respondents agree that global adoption of 3D printing can challenge China's position as a global manufacturing leader.¹¹

A report by ING Bank predicts that 50 percent of manufacturing will be 3D printed in 2060 in scenario I, with approximately that number being achieved as early as 2040 in scenario II.¹² This report estimates that 3D printing will wipe out almost one-quarter of world trade as of 2060 in scenario I and two-fifths in scenario II. The greatest impact of the reduction in world trade would be on automobiles, industrial machinery, consumer products, and on trade with China.¹³

Table 1 lists areas where 3D printing has a high potential to disrupt traditional manufacturers, supply chains, and consumers. 3D printing will generate the highest degree of disruption where consumers either require or desire customized products, average production volumes are low, markets are small and fragmented, the end product requires complex assembly, prediction of demand is difficult, and raw material costs and scrap rates are high. The degree of disruption will intensify as the use of 3D printing extends from manufacturing prototypes to traditional product manufacturing, as new

Managing the Disruptive Effects of 3D Printing

printing materials and applications are created and as the price of 3D equipment and material decreases.

Table 1. Broad Product Categories Where 3D Printing Has High Potential to Become a Disruptive Innovation

3D Printing is likely to have the greatest negative impact for these product categories:

- Goods requiring high degrees of customization
- Complex mechanical parts requiring assembly
- Goods that benefit from the consolidation of multiple components into a single product
- Goods with high tooling and mold costs
- Goods for small, fragmented markets
- Emergency shipments
- Prototypes
- Goods requiring fast delivery (spare parts, emergency shipments, product recall replacements)
- Spare parts
- Product recall replacements
- Hobbyist applications
- Goods where demand estimation is difficult
- Goods with high inventory holding costs due to low turnover, long shipping distances, short product life cycles and high markdowns
- Goods made with high cost materials that have high scrap rates
- Goods that are large and/or heavy

3D Printing is likely to negatively impact the following industries:

- Manufacturers of mass production based equipment
- Traditional warehouses
- Short and long distance transportation services

The aerospace, automotive, and mechatronic industries may be subject to higher levels of disruption due to the complex and highly detailed nature of their products.¹⁴ Another report predicts that aerospace, automotive, medical, architecture and retail industries will be most affected by 3D printing.¹⁵

The Chinese economy may be subject to high disruption as its manufacturing is based on economies of scale and the use of low-skilled assembly workers.¹⁶ Logistics firms could also incur potential large losses due

to 3D's local production capabilities and the reduced need for warehouses. The demand for traditional manufacturing-based die-casting, drilling, lathe-turning and molds will also decline as 3D printing becomes more popular.¹⁷

3D printing's ability to integrate many components into one product has major implications for supply chain relationships. With traditional manufacturing, multiple suppliers are typically used for complex products. In contrast, with 3D printing, the entire assembly must be purchased from one supplier.¹⁸

3D Printing Contrasted with Mass Production and Mass Customization

Mass production is built on a design, build, and deliver model. In mass production savings from large production volumes and from low labor costs are used to offset high transportation and inventory holding costs. In contrast, 3D printing can produce small quantities at low cost as (1) there is no need for molds, cutting, lathing, or grinding; (2) production is based on actual orders; costs and risks associated with unsold inventory are drastically reduced, (3) the separation of design and manufacturing enables local production, which further reduces transportation and warehousing costs, and (4) there are no labor costs associated with the assembly of complex components.

3D printing and mass customization are frequently compared with one another. In both 3D printing and mass customization, highly customized products can be built at low cost, products are built only after an order is placed, single unit or low volume production is utilized, and inventory holding risks and costs are substantially reduced.

Mass customization achieves low-cost customization by using standardized components put together in different combinations. 3D printing achieves low-cost customization via automated manufacturing, specialized designs, and the use of different materials. In contrast to the semi-finished parts and component parts used in mass customization, 3D printing produces goods using powders, filament coils, plastics, resins, polymers, metals, ceramics, nylon fibers, and materials similar to human cells. While mass customization often uses off-shore production and assembly to reduce labor costs, goods made by 3D printing can be locally produced. Product design and manufacturing functions are typically performed by a single firm in mass customization. In contrast, 3D printing enables final consumers as well as third parties to produce a product.

Advantages of 3D Printing in Comparison to Traditional Manufacturing

The following section examines the major advantages of 3D printing over traditional manufacturing. These advantages include: (1) high speed to market and fast delivery, (2) the ability to economically produce components which require complex tooling, (3) savings in shipping, warehousing, and other inventory holding costs, (4) the ability to economically produce customized designs, and serve small fragmented markets at low cost, (5) the high degree of manufacturing flexibility, and (6) the reduction in a firm's carbon footprint.

High Speed to Market

One report found that in the time required to produce one new product version with traditional manufacturing, 19 iterations can be completed with 3D printing.¹⁹ Additive 3D printing can generate a fully functional model with gears in hours or days versus weeks with traditional manufacturing processes.²⁰ 3D printing also has speed-to-market advantages due to its ability to produce goods locally. This reduces the need for large in-transit inventories.

The Ability to Economically Produce Complex Parts Which Would Require Complex Tooling Using Traditional Manufacturing Processes

3D printing enables complex parts, such as gears, to be produced without assembly, tools, or molds. 3D printing also reduces the number of component parts. Prior to upgrading to 3D printing, GE Aviation's LEAP jet engine nozzles were made from 20 separately cast parts that needed to be individually assembled. In contrast, nozzles produced by 3D printing consist of only one component.²¹ GE found that manufacturing costs of 3D printed parts were 75 percent less than the costs of conventional manufacturing.²² In addition, a 3D manufactured nozzle is 25 percent lighter and five times more durable than the part it replaced.²³ Similarly, GE's new Catalyst turboprop engine design combined 855 separate parts into 12 using 3D printing.²⁴

Savings in Shipping, Warehousing and Other Inventory Holding Costs

The separation of design and production in 3D printing enables firms to produce goods locally and to outsource production to final and organizational customers such as stores, fab shops, and providers of logistics services. Localized production reduces the need for warehouses and minimizes in-transit pipeline inventories. The advantages associated with lower inventory holding costs are particularly applicable to firms that

produce or transport large and/or heavy components, to products with high obsolescence rates, to products subject to price reductions, and in situations where it is difficult to accurately forecast demand.

Users can download CAD designs to produce 3D designed products on site (including final and organizational customers). Many items such as household products, toys, and jewelry can be made in one's home. In-store production can occur in a retailer's facility where customers can design their own customized goods. Production can also be completed by fab shops, such as Shapeways, that maintain a catalog of part CAD designs, produce goods, collect payment and ship goods. Logistics carriers are also increasingly fulfilling 3D based production. UPS, Fed Ex, RSA Global, and PostNord are in the process of turning their airport-based warehouses into mini 3D factories.

The Ability to Economically Produce Customized Products and Service Small Fragmented Markets with Uncertain Demand

Highly customized parts and small production runs can be less costly with 3D printing than with traditional manufacturing as there are no upfront tooling costs.²⁵ To consumers, on-demand production results in getting the exact style, specifications, and product characteristics desired. With 3D printing there is also no need to stockpile large inventories or undertake significant markdowns due to uncertainty in predicting demand.

A High Degree of Manufacturing Flexibility

Unlike traditional manufacturing, 3D printing is not constrained by large inventories of component parts or finished goods or by special application machinery. Supplies of resins, polymers, fibers, and filament coils on hand are much more flexible in usage than that of finished goods or component parts. 3D manufacturing flexibility increases a firm's ability to profitably serve niche markets, to quickly respond to unanticipated demand, and to shift production capacity among products and markets.

Reduction in a Firm's Carbon Footprint

3D printing enables firms to reduce their carbon footprint in comparison with mass production due to the use of hollow parts, less scrap, lower weight, fewer assembly operations, less transportation, and better recycling opportunities due to the use of only one material in production. Reduced scrap is particularly important for plastics where recycling rates are low and recycling transportation costs are high as compared with other materials.²⁶ Researchers at Michigan Technological University analyzed the resources needed to manufacture objects in an overseas factory and to ship them to the U.S. versus local manufacture using 3D printing. The researchers found that

3D printing used 41 to 64 percent less energy due to material savings and reduced shipping.²⁷ Researchers at Delft University of Technology predicted that 3D printing could reduce global energy usage by 25 percent as of 2050.²⁸

Applications of 3D Printing for Hearing Aids, Spare Parts and Dental Products

This section examines the successful use of 3D printing in three applications: hearing aids, spare parts, and dental products. Each of these 3D applications utilizes a different set of benefits associated with 3D printing: customization for hearing aids, reduction in inventory holding costs and faster delivery speed for spare parts, and a combination of customization, delivery speed and lower costs for dental products.

While this section concentrates on these three industries, 3D's disruptive technology will also affect a number of industries including healthcare, transportation, manufacturing, aerospace and architecture. The large number and range of industries affected by 3D printing are due to the ability of 3D printing to use different materials, including living tissue, rubber, metals, plastics, and wood fiber in a single print run.²⁹

Hearing Aids

The production of hearing aids via 3D printing was a very early use of 3D printing in a high-volume application. In 2000 Sonova, a Swiss hearing aid manufacturer, collaborated with Materialize NV, a Belgian-based 3D printing company, to develop Rapid Shell Modeling (RSM) software. This software automated the design of customized hearing aid shells.³⁰

Prior to 3D printing, nine steps were required to produce a mold. In contrast, 3D printing requires only three steps: scanning, modeling and printing. The 3D scan uses 100,000 to 150,000 points of reference which result in better fit and comfort in comparison with traditional manufacturing.³¹ 3D printing has had a major impact on the hearing aid industry in terms of its market share and adoption speed. In less than two years, traditional manufacturing has been virtually eliminated from the hearing aid industry in favor of 3D printing.³² Currently, 99 percent of hearing aids manufactured worldwide use 3D technology.³³

Spare Parts

Spare parts manufacturing is an ideal application of 3D printing due to the unpredictable demand for spare parts, small production runs, and the need for fast delivery. Inventory holding costs are high due to drastic reductions in the value of existing spare parts as existing machines are replaced with new models. With traditional manufacturing, spare parts are warehoused in anticipation of need. In contrast, with 3D based manufacturing, spare parts are made as needed. The use of 3D printing reduces or eliminates uncertainty in demand. 3D printing also enables firms to profitably print parts for appliances that are no longer produced.

According to one report, 85 percent of spare parts suppliers will adopt 3D printing as of 2022.³⁴ Survey respondents estimate that spare parts suppliers will save over \$3 billion annually using 3D technology as compared with traditional mass production.³⁵ Another study of 38 German industrial companies found that 85 percent of spare parts suppliers plan to fully integrate 3D printing into their workflows within the next five years.³⁶

Some manufacturers enable end users to produce spare parts by on site fabrication. On site production reduces transportation costs, ensures the timely replacement of faulty parts, and enables end users to produce spare parts on-demand with little or no finished goods inventory. As an example, Mercedes Benz allows its local dealers to print 3D spare parts in the dealers' shops. Firms like Whirlpool have partnered with Spare Parts 3D, a startup that digitizes spare parts manufacturing via 3D printing.

Dental Applications

Laser scanners are now able to create a 3D model of a person's teeth and calculate models for dental crowns, night guards, dental veneers, retainers, implants, and bridges, crowns, and invisible braces. In dental and medical applications, as with hearing aids, physical impressions are being replaced with a more precise 3D impression. After a patient's mouth is scanned at a dentist's office, the scans can be sent to a 3D printer located at the dentist's office, at a 3D printer shared by dentists, or to a service bureau for processing. While making a bridge or denture using traditional methods can take two to three weeks, the production cycle using a 3D printer is two to three days.

Smile Direct Club creates custom dental aligners via teledentistry without the need for a patient to visit a dentist's office. Smile Direct Club has had over 750,000 patients and is licensed in all 50 states. A market research firm estimates that the 3D printing market for the dental field will reach \$930 million by the end of 2025, which is a 17 percent compound growth rate.³⁷

While setting up a traditional in-house dental lab typically costs upwards of \$100,000 a suitable medical grade 3D printer now costs around \$20,000.³⁸

Managing the Disruptive Effects of 3D Printing

A market research firm estimates that the additive manufacturing market for the dental field will grow from \$780 million per year in 2015 to over \$3.1 billion in 2020.³⁹

All three applications utilize the on-demand manufacturing capability of 3D printing. This results in lower inventory holding costs, lower markdowns of unsold finished goods, and the production of goods that are highly customized for the individual consumer.

Managerial Issues in Planning for The Adoption and Implementation of 3D Printing

Firms have different degrees of readiness in adopting 3D printing. An Ernst & Young survey of 900 companies from 12 countries and 9 industries found that that 24 per cent of companies are already applying 3D printing, and an additional 12 percent are considering 3D printing. In contrast, 11 percent of respondents stated they are testing and experimenting with 3D printing, 8 percent have 3D championing departments (generally R&D and engineering departments), and 3 percent have significant experience in 3D printing and a clear strategic plan at the highest management level for its future application. One in three respondents state that lack of information about 3D printing technology is holding them back.⁴⁰

Evaluating a Firm's Vulnerability to 3D Printing by Competitors

The first step in planning for the adoption of 3D printing is to determine a firm's vulnerability to 3D-based competitors. An Accenture study classifies a firm's vulnerability to a disruptive technology into one of four categories: durability, vulnerability, volatility, and viability.⁴¹ In the durability stage, firms view 3D printing as a distant threat as they mistakenly view 3D's market prospects as small and limited.⁴² In the durability stage firms need to continually monitor the growth of 3D printing and to begin to focus on appropriate competitive actions and growth opportunities. While incumbents are aware of the impact of 3D printing in the vulnerability stage, they view 3D printing as a short-run disruption.

In volatility, large disruptors enter the market with new sources of value. Incumbents need to plan catch-up strategies through large investments in 3D printing and through recasting their overall supply chain strategy. In viability, past strategies that were effective in combatting competitors are now ineffective for persistent disruptors. Since 3D printing requires different competencies than traditional manufacturing, new firms may be better equipped to engage in 3D printing than existing firms.⁴³

Strategies to Counter Competitors Using 3D Printing

Table 2 describes four strategies firms can use to effectively compete against 3D printing-based competitors: focus (niche), mass customization, inventory-based, and outsourcing. The degree of organizational commitment necessary to implement each strategy differs.

A firm can use several of these strategies simultaneously. For example, it can use 3D printing for prototype development, employ mass customization for products comprised of different combinations of mass-produced parts, and outsource spare parts fulfillment to a logistics carrier. The choice of strategy can be based on inventory holding costs, customer desire for customization, and the need for emergency shipments.

A focus strategy appeals to small fragmented market segments with highly specialized needs. A focus strategy is a viable alternative to 3D printing when a market is small and fragmented, where a narrow product line is an attractive alternative to customized products, and where the market segment is large enough to be profitable. While mass production techniques can be used by firms adopting a focus strategy, product choice alternatives are limited. The focus strategy is not suitable for prototypes, spare parts, hobby, medical and dental applications where items need to be customized.

Unlike a focus strategy, mass customization seeks to satisfy a customer's specific needs through the mass production of component parts assembled to a customer's specifications. Mass customization has significant advantages over the focus strategy in reducing inventory holding costs. While mass customization requires that a firm rethink and recast its design and production strategy, it is much less of a departure from traditional manufacturing than 3D printing.

A third strategy seeks to reduce inventory holding costs through local production and just-in-time inventory management. This strategy reduces inventory holding costs by limiting styles, colors, and product feature alternatives to the fastest-selling goods. While just-in-time inventory management can also be used to reduce inventory, this requires that a firm's supply chain network become relationship versus transactional-based. These inventory management-based strategies do not fulfill customization needs.

The final strategy involves outsourcing of either 3D design and/or production. This overall strategy benefits from the expertise of the outsource firm. Outsourcing that is based on local production facilities can reduce travel time, inventory requirements, and pollution. The outsourcing of 3D design and/or manufacture is an appropriate alternative to firms in the early stages of adopting 3D printing or to firms that use 3D printing on an occasional basis such as in prototype or spare parts manufacture.⁴⁴ There are several variations in the use of 3D outsourcing. End users can rent 3D

Managing the Disruptive Effects of 3D Printing

capacity from service bureaus. These service bureaus can also operate 3D machines located in a manufacturer's facility or in the service bureau's home location. In some cases, equipment providers have operated as service bureaus by printing products for end users.⁴⁵

Table 2. Strategies Firms Can Use to Compete Effectively Against 3D Printing-Based Competitors

Niche/Focus Based Strategies

Appealing to Niche/Focus Markets:

- ✓ Appeal to niche/focus markets through specialized products and services

Mass Customization-Based Strategies

Using Mass Customization:

- ✓ Ability to produce highly customized products at low costs
- ✓ Ability to better serve small and fragmented markets
- ✓ Increased manufacturing flexibility
- ✓ Reduced inventory requirements and markdowns

Inventory Based Strategies

Using Local Production for Mass Produced Goods:

- ✓ Appeal to niche markets as opposed to customized products based on consumer demand
- ✓ Reduction of shipping, warehousing, and other inventory holding costs
- ✓ Reduction of a firm's carbon footprint due to lower emissions from trucks, planes, etc.
- ✓ Promotion of domestic employment

Utilizing Just-in-Time Inventory Management for Mass Produced Goods:

- ✓ Increased delivery speed
- ✓ Reduction of warehousing and inventory holding costs

Outsourcing 3D Printing Based Strategies

Outsourcing 3D Printing Design and Production:

- ✓ Obtain benefits of 3D printing at lower required investment
- ✓ Reliance of expertise of external service providers
- ✓ Reduction of costs due to expertise of outsourcers
- ✓ Lower investment\ requirements
- ✓ Use of local facilities for design and production reduces travel time, inventory requirements, and pollution

Addressing Intellectual Property and Quality Control Issues Associated with the Separation of Design and Manufacturing

There are major intellectual property and quality control concerns associated with outsourcing 3D printing due to the separation of design and manufacturing. Since the ease of copying by 3D printing is similar to what occurred when MP3 music files became popular, manufacturers and consumers need to distinguish 3D originals from counterfeits. This can be accomplished by RFID chips and copy control (which is similar to digital rights management applied to music files) and Identify 3D. Identify 3D ensures authorized use of files and traceability throughout the entire production process. The separation of design and production also requires managing third party manufacturers in terms of quality control and counterfeit surveillance.

The concern for quality standards is critical for products with potential safety issues and for products produced by highly diverse or inexperienced individuals.⁴⁶ Outsourcing standards need to reflect that some parts may require post-processing operations such as cleaning, washing, and inspected.⁴⁷ The accuracy of product designs, material choice, and worker training also needs to be assessed.

Summary and Conclusion

A major factor contributing to the disruption potential of 3D printing is its capacity to change a firm's value proposition. While the competitive advantages in mass production are based on low cost, focus, and differentiation strategies, the advantages associated with 3D printing are based on low cost, highly customized products, faster prototype development times, lower inventory holding costs, and highly flexible production facilities.

3D printing has a major impact on a firm's strategic planning. With traditional manufacturing, firms typically based their organization's mission on products, served markets, and technology. Unlike mass production where component parts and molds were directed at a narrow category of goods, the materials and processes used in 3D printing can be directed towards a very broad category of goods and markets. 3D printing also enables a firm to quickly adapt its materials and production capabilities from mature to fast-growing products.

The adoption of 3D printing requires that firms reevaluate their supply chain responsibilities. The role of a supplier under 3D printing may change from a provider of finished goods to a CAD designer. Parts suppliers also have new roles as 3D printing requires fewer suppliers due to the integration of multiple parts into a single unit. Traditional logistics providers also need to

Managing the Disruptive Effects of 3D Printing

undertake new roles such as producing replacement parts at an airport facility.⁴⁸

The transition from traditional production to 3D printing from prototypes to a broad category of goods will be a difficult one for many companies. With prototypes, a firm focuses its attention on a single unit as opposed to an entire product line. Goods produced via 3D printing typically involve custom goods, and the firm's ability to satisfy constantly changing customer demands. In addition, large scale manufacturing of goods via 3D printing requires managing third party manufacturers in terms of quality control, counterfeit surveillance, and delivery speed issues.

The increased importance of 3D printing opens up academic research possibilities. These include the impact of 3D printing on logistics and supply chains, the impact of local production on the environment, and production planning difficulties associated with a firm's utilizing both mass production and 3D printing.

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Managing the Disruptive Effects of 3D Printing

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