Elsevier Editorial System(tm) for Technological Forecasting & Social Change
Manuscript Draft

Manuscript Number:

Title: Proprietary Benefits from Open Communities: How MakerBot Leveraged Thingiverse in 3D Printing

Article Type: Special Issue: Digital fabrication

Keywords: 3D printing; online communities; ecosystems; open source; open design

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1. Introduction

For decades, the incentives to create and diffuse innovations have been associated with the strength of appropriability regimes and the ability of a private inventor to appropriate private returns from their economic investment. Traditionally this has been associated with strong IP protection mechanisms, such as the use of patents, copyright and trade secrets (Nordhaus, 1969; Teece, 1986).

However, this view was disrupted by the emergence in the late 20th century of the open source software innovation model. This "private-collective" model of innovation focuses on a shared good that is produced through the cooperative efforts of economically rational private actors, who both benefit from the efficiency of shared production while seeking private gain (Perens, 1999; von Hippel & von Krogh, 2003). Although this community model is best known (and researched) for software, others have sought to apply it both to other information goods and to tangible goods such as computer hardware (Nov, 2007; Raasch et al, 2009).

In response, some previously proprietary incumbent firms have experimented with opening parts of their complex offerings to win cooperation from adopters, complementors and even rivals (West, 2003; Henkel, 2006, Shah, 2006; West & O'Mahony, 2008; Spaeth et al, 2010). The availability of shared IP from an open source community has also enabled the formation and entry of new firms that build upon the collective efforts (Gruber & Henkel, 2006; Dahlander, 2007). However, there are numerous unanswered questions about the viability of such hybrid models, including how firms can position themselves initially to leverage open source models of innovation, and when and how they can use a closed IP strategy to strengthen the appropriability without a backlash from open user communities.

This study considers these questions in the context of 3D printing, an industry that began 30 years ago with multiple entrepreneurial startups formed around nine competing patented approaches to serve niche industrial markets. In the first two decades, the industry grew slowly as price and other factors limited its suitability for broader commercial and consumer markets. Its widespread availability to consumers did not come until the expiration of some of the earliest patents and the formation of RepRap, an open source hardware community — a community that directly enabled the entry of startups that made consumer products out of the open designs.

One of the most successful of these consumer startups was MakerBot Industries. Beginning with its founding in 2009, MakerBot and its founders used a three phase strategy to stimulate demand for its products. First, they created Thingiverse as an online community for sharing user-generated digital content and designs compatible with open source hardware such as RepRap's 3D printer. Next, they sold a self-assembled kit developed as a fork of RepRap, making it affordable for makers to own a 3D printer. Finally, they evolved their products as closed source hardware and software, using proprietary enhancements and improved integration to reach a broader user base than competitors while keeping the design ecosystem as open source.

The paper is organized as follows. First it reviews prior research related to proprietary, open and community models of innovation. Next, it reviews the history of the 3D printing industry, including entrepreneurial entry by industrial- and consumer-focused 3D printing companies. From this, it traces the strategy of how MakerBot and its Thingiverse community created demand for 3D printers among consumers. It concludes with a discussion of the implications for partly open strategies in a world of both digital designs and tangible products.

2. Prior Research

2.1 Adoption of Systems and Platforms

Innovations are adopted based on their characteristics, and also the characteristics of their adopters. In particular, earlier adopters (such as hobbyists or other enthusiasts) are more eager to try new technologies without proven benefits and tolerant of usage difficulties (Rogers, 1995). In many cases, the value of the innovation depends on the provision of certain complementary assets that make the innovation more valuable (Teece, 1986).

Systemic innovation is different from other kinds of innovation, in that the value received by the adopter depends on the value of the overall system. While the performance of most innovations improves with technological advances, the overall value of the system is limited by certain lagging technical and institutional attributes that Hughes (1983, 1987) terms "reverse salients." Promoters of a systemic innovation face the challenge in combining and coordinating the production and adoption of different components of the system by external actors (Maula et al., 2006). In relation to open innovation, systematic innovation entails boundary management (Jarvenpaa & Lang, 2011, Teigland et al., forthcoming) within and across the borders of firms. Some of these components are proprietary and others open source, which are subject to different licensing regimes. The configural arrangement of these components not only has ramification at the product level but also on the ways firms organizing to profit from such an arrangement.

A particular type of systemic innovation is a platform, which has two key attributes. The platform provides well-defined interfaces that enable third parties to provide complementary goods (such as "apps") for the platform, and the platform sponsor nurtures an ecosystem of firms (or individuals) who supply such complements (Gawer, 2009). Sponsors selectively provide openness — in some parts of their technology but not others — to attract both adopters and a supply of complements while retaining enough proprietary control to extract profits from the platform (West, 2003; Boudreau, 2010).

2.2 User and firm sponsored communities

External user communities have been increasingly important to firms in this digital economy. For firms, communities can provide a source of complementary goods (Jeppesen & Frederiksen, 2006), support (Lakhani & Von Hippel, 2003), bug reports (Dahlander & Magnusson, 2008) and marketing feedback (Schau et al, 2009). For would-be entrepreneurs, the firm-sponsored communities of today's "app economy" provides an opportunity to develop and diffuse new add-on products (MacMillan et al, 2009). In fact, for many years communities have supplied both the knowledge and entrepreneurs that enable the creation of new firms by user-entrepreneurs (Dahlander, 2007; Shah & Tripsas, 2007; Haefliger et al, 2010). Of particular relevance to this study are two types of communities, those that produce open source software and those that seek to apply these principles to hardware.

Open Source Software. While the widespread availability and use of online communities has been fueled by the Internet, extant research on firm-sponsored communities has been heavily skewed towards free and open source software (Lakhani & von Hippel, 2003; Shah, 2006;

Dahlander & Magnusson, 2008). Such communities are characterized by a standard form of IP license, a form of cooperative production and a mechanism of governance (Perens, 1999; West & O'Mahony, 2008). For free software communities, the emphasis is on a particular type of license (the GNU Public License or GPL) that supports an ideology of continual sharing and the objectives of the free software movement (Stallman, 2002; West, 2003; Lakhani & Wolf, 2005).

Open source communities have helped create firms, by providing the technology necessary for entrepreneurial entrants to provide new offerings (Gruber & Henkel, 2006; Dahlander, 2007; Piva et al., 2012); in many cases, these firms create their offerings by "forking" off a proprietary version from the community's shared source code. At the same time, firms can also create communities, with rules and ongoing sponsorship to keep the community activity aligned to support the firm's objectives, such as by promoting the firm's offerings or providing complements (Dahlander & Magnusson, 2005; Shah, 2006; West & O'Mahony, 2008).

Although the production (and use) processes are different, online communities have been successfully organized to produce other kinds of information goods. This includes online information (Nov, 2007), musical sounds (Jeppesen & Frederiksen, 2006) and video games (Jeppesen & Molin, 2003). These communities have also demonstrated the firm spawning (Haefliger et al., 2010) and firm sponsorship (Jeppesen & Frederiksen, 2006) dynamics noted in open source software.

Open Source Hardware. Enthusiasts have sought to replicate the success of open source software in communities that produce computer hardware and other tangible goods. These efforts — variously termed open design, open hardware design or open source hardware — are often organized using processes and principles directly modeled on open source software. This includes modularization to minimize complexity, adapting open source IP licenses, a culture of collaboration, and the selective use of openness by project sponsors. Compared to the production of software or other information goods, however, open source projects producing hardware have higher barriers to entry and collaboration inertia, and a greater role for firms in providing needed infrastructure such as manufacturing (Balka, Raasch and Herstatt, 2009, 2010; Raasch, Balka & Herstatt, 2009).

Among IT enthusiasts and entrepreneurs has been an effort to formalize the definition of "Open Source Hardware", explicitly modeling the better known software example of the Open Source Definition (Perens, 1999). Starting in 2007, various organizations proposed a variety of open hardware licenses (analogous to their software counterparts), and creating an "Open Source Hardware Definition" modeled on the software predecessor (OSHWA, 2013).

2.3 Research Design

Our interest is in understanding the interaction between user and open innovation in open (hardware) design communities. To date, these communities have achieved neither the economic success nor academic attention of their software counterparts.

We have chosen to study the field of consumer 3D printing for three reasons. First, it seems to be among the first open design efforts to gain public adoption and commercial success, having made considerable progress since Raasch et al (2009). Secondly, 3D printing provides a direct link between the production of tangible goods to the digital world of computer-mediated collaboration. Finally, 3D printing is an enabling technology that has the potential to unleash a wave of individual and small business experimentation and innovation, vanquishing entry barriers much as personal computers and open source software did for information technologies.

To better develop theory and be able answer "how" and "why" questions, we sought an exploratory research approach using a qualitative case study (cf. Yin, 2009; Eisenhardt &

Graebner, 2007). Information on the evolution of the firms and technology is taken from a variety of secondary sources, including technical articles and books (e.g. Jacobs, 1992) news articles, FundingUniverse.com, company websites and patents; particularly helpful were the annual reports on 3D printing by Wohlers Associates. Information on the RepRap Project, MakerBot and Thingiverse were taken from the community wikis and discussion group; key postings of the RepRap Project from 2005-2011 are compiled in Hodgson (2012).

3. Context: 3D Printing

The context of this study is 3D printing (3DP), a family of additive manufacturing technologies that allow the translation of digital designs into physical objects via a computer-controlled custom manufacturing device. While "3D printing" once referred to a specific process invented by MIT, today the term is used in a more generic sense to include a range of additive manufacturing technologies.[1]

The 3D printers had three initial applications: rapid prototyping, making molds for high-volume production and direct short-run production. The technology faced considerable technological and entrepreneurial ferment for two decades while serving niche industrial design markets, until the consumer market was enabled by an open design project and the entry of a new round of startups.

3.1 Invention and Industrial Applications of 3D Printing

A series of additive manufacturing technologies were invented in the 20th century, most by U.S. inventors during the late 1980s (Table 1). During this period, none emerged as a clear dominant design that displaced the others, with market share fragmented between three or more

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[1] The summary of the key technologies is taken from the technical literature, including Wohlers (1992), Jacobs (1992; 1996), Kruth et al (1998), and Gibson et al (2010).

technologies. All of these approaches involve creating a 3-D object as a series of thin two-dimensional layers, one on top of another. These technologies were either invented by academic researchers, or individual inventors who then went on to found startups to commercialize the technology (Table 2).

Two of the major technologies involve having light focused to melt the input material at a specific location. Stereolithography (SLA) involves shining an ultraviolet light on a liquid resin at a particular location to harden the liquid into plastic at that location. It was invented by Chuck Hill, who, when the first patent was granted in 1986, left his employer to found 3D Systems.

In parallel, Carl Deckard (a PhD student at the University of Texas) invented Selective Laser Sintering (SLS). This technology uses an infrared laser to fuse a plastic or metal powder, but requires an inert nitrogen atmosphere to avoid combustion; it was an important technology during the early years of 3DP as it was the first technology to directly produce metal objects. UT Austin was granted a series of patents beginning in 1989, and licensed the patents to a number of spinoff firms. Deckard cofounded DTM Corporation, which operated a 3DP service bureau starting in 1988 and sold its first printer products to industrial customers in 1992.[2]

Others adapted 2-D inkjet printing to build up 3D objects. This included MIT professor Emanuel (Ely) Sachs, who with his researchers was granted more than a dozen patents from 1993 to 2006, in a process called “3D Printing”[3] that MIT licensed to eight spinoff companies in the 1990s (Shane, 2000). Other variants included Inkjet Printing, a low-cost system from Sanders

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[2] Other metal fabrication techniques emerged in the 1990s. Independent inventor Ralf Larson worked with Chalmers University of Technology to replace the laser of SLS with an electron beam and create Electron Beam Melting (EBM), while other researchers modified FDM to use spools of metal filament.

[3] According to US Patent & Trademark Office databases, MIT also applied to trademark “3DP” and a 3DP logo in 1992, but abandoned the application in 1994.

Prototype for printing wax molds for jewelry and dental applications, and PolyJet, used in printers from Israel's Objet to print hundreds of rows of photo-sensitive polymer plastics.

An even simpler approach came from S. Scott Crump, who after tinkering with making objects with a glue gun formed Stratasys in 1988, filing his first of many patents in 1989. The Fused Deposition Modeling (FDM) combined the mechanical advantages of the nozzle approach of inkjet printing with a stable feedstock (a spool of plastic). Because Stratasys filed a trademark on the phrase and acronym, some vendors used the term Fused Filament Fabrication as a generic synonym. Perhaps the most unusual system came from inventor Michael Feygin, who cut out and layered paper sheets to create wood-like structures in a process called Laminated Object Modeling (LOM); Feygin formed Hydronetics (later Helisys) to commercialize the technology and (like DTM) received early SBIR funding from the NSF Strategic Manufacturing Initiative.

In the industry's first decade, two companies — 3D Systems and Stratasys — were able to go public, gaining both one-time and ongoing access to capital, as well as increased public visibility. Helisys went public in 1996 but lost money until it failed in 2000. The surviving first generation companies were acquired between 2001-2012 by one of the two market leaders.[4]

In its first five years, 3D Systems captured 73% of the global market by unit sales (Wohlers, 1992). However, it struggled for years to find a large enough market to support its growth and generate consistent profits (Pendleton, 1994; Brooks, 1997). It took a decade of product sales, until in 1997 more than 1,000 systems units were sold worldwide in a single year; in that same year four technologies (SLA, IJP, FDM, LOM) each had between 15-26% market share, with Stratasys the market leader at 25% share (Kruth et al, 1998).

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[4] When Stratasys merged with Objet in December 2012, their respective shareholders split the combined equity 55/45. The successor company kept the Stratasys's name and NASDAQ stock listing but, like Objet, was incorporated in Israel.

3.2 Classifying Barriers to Adoption

While the inventors were successful in creating new technologies, winning patents and (to a limited degree) attracting venture investment, they faced a long, slow road to win widespread adoption — which (judging from early predictions) came much more slowly than expected.

As with the evolution of other complex systems technologies, at different times different aspects of the system proved to be a limiting factor in the adoption of the technology (cf. Davies, 1996). We identify six broader categories of such limits (Table 3) corresponding to the reverse salients defined by Hughes (1983, 1987). Addressing these limits thus attracted the attention of firms, managers and inventors seeking to improve system attractiveness and increase adoption.

Two of these related directly to the products of the 3DP manufacturers. The most obvious was **printer performance.** In the initial generation of systems, all of the academic and industrial inventors faced a number of key challenges (Jacobs, 1992, 1996). Most materials were subject to shrinkage or curling as they dried, and practical throughput was limited by how much the drying process could be accelerated. Complex cantilevered shapes might not be properly supported as the layers were created, and so new software algorithms were required to work around the mechanical limitations of the in-progress production.

The other key printer limitation was **cost.** When compared to traditional manufacturing, 3DP requires almost no setup costs (beyond the design). However, it was too slow and too expensive (per unit) for high volume production and (initially) not durable enough for some types of components. Given these constraints, the initial applications for 3DP focused on two areas: rapid design and prototyping, and then taking those designs to create original molds for subsequent molding or casting (Jacobs, 1996). For industrial applications, 3DP replaced casting, machining (cutting), or bending metal into a desired shape. For consumer products, 3DP replaced injection molding of plastic. Even so, the high purchase prices for such printers limited their sale to medium and larger firms that were willing to pay $100,000 to $500,000 (later $50,000 to $300,000) in exchange for rapid turnaround on product designs.

Some of these limits were under less direct control by the 3DP manufacturers. For example, **computer performance** improved dramatically during the period 1986-2013, thanks to orders of magnitude improvements in speed, capacity and cost due to Moore's Law and other factors.

The initial 3DP customers were those industrial manufacturers seeking rapid prototyping (cf. Jacobs, 1992). Printer manufacturers sought to tap into existing design processes and workflows, and so they designed their systems to produce objects created by existing **application software,** notably CAD (Computer-Aided Design) design software.

To access these processes and workflows, the 3DP firms needed a way to interoperate with such CAD programs. This was made possible by 3D Systems, which in 1987 created the STL file format, which quickly became the *de facto* standard for digitally defining the surface of a three-dimensional object using a series of triangular facets (Jacobs, 1996: 123). This standard interchange format provided a mechanism for communicating between CAD and other three-dimensional graphics applications that created digital designs, and drivers that rendered such designs into physical objects. It was quickly adopted as the least common denominator export format for 3DP, and remains in use 25 years later.[5]

Two other categories of reverse salients attracted increasing attention by 3DP firms seeking to move beyond their initial based of industrial designers, by adopting more of a systemic or ecosystem-level approach to creating value for prospective buyers. As with PCs, one of these was **ease of use.** Some of this ease of use was directly under firm control, as they made printers

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5 Some have referred to STL as analogous to the PCL or PostScript printer languages, but its simplicity is more comparable to the HP-GL pen plotter language of the 1970s. Given its limitations, there have been various efforts to supplant it with a more complex file format (e.g., the ISO-sanctioned Additive Manufacturing File Format), but thus far such efforts have not been successful.

more reliable, self-monitoring and straightforward to use. However, for broader markets, the software ease of use became a limiting factor, requiring improved graphical user interfaces (both by 3DP firms and application providers). Finally, for the mass market, mere technical connectivity was not enough: 3DP firms needed to assume responsibility for end-to-end operability, by increasing the integration of all the elements of the system.

Finally, as with many other classes of hardware (such as traditional 2D printers), the market for 3DP depended on the availability of **content**: the purchase of a 3DP created value only when the buyer had digital designs that could be converted to tangible goods by the 3DP system. For initial buyers such as industrial designers, this content was generated by the user. Over time, catalogs began to emerge of digital designs for standardized physical objects (such as nuts and bolts). The rise of the consumer market also fueled (and was fueled by) user communities formed to share user-generated content. One of the most prominent of such communities was Thingiverse, discussed below.

3.3 Consumer Market

For years, futurists and other analysts predicted that 3DP would become cheap enough to become available to consumers, much as personal computers made computing available to consumers. By 2013, the consumer segment had developed to the point that dozens of hobbyist-oriented models were sold at prices ranging from $300 to $3000 (*Make*, 2013). The rising popularity prompted speculation that the world's largest PC printer manufacturer, Hewlett-Packard, would enter (and thus legitimate) the 3DP market the way that IBM had done with personal computers three decades earlier.

As with the PC industry, winning widespread adoption of 3DP meant addressing key reverse salients, including software applications and ease of use. As with 2D printing, demand for 3DP required content, including user-developed content (from graphics programs), the ability to input designs (via scanning) and libraries of pre-defined content. At the same time, consumer adoption of 3DP depended on improvements in computing performance.

As with personal computers, penetration of the consumer market began with the hobbyist market, in this case dedicated aficionados of what during the early 21st century was termed the “maker” movement (Anderson, 2012). Consistent with Rogers (1995), these earliest adopters were (when compared to other consumers) the most motivated and tolerant of performance limitations, complexity and (relatively) high costs.

However, the impetus for the eventual consumer market for 3DP came not from any one firm, but from the diffusion of technology (and concomitant cost reduction) provided by a 3DP open design community. The RepRap Project was announced in March 2005 by Adrian Bowyer, a UK mechanical engineering professor. He used the commercial Stratasys printer in his lab both for experiments and to fabricate parts, and used his experience with the more expensive 3DP designs to suggest a variety of inexpensive nozzles for an FDM-based system.

Starting at a time when many of the original industry patents were reaching their 17-year expiration date, Bowyer created IP rules consistent with open source software and open design communities (cf. West & O’Mahony, 2008; Raasch et al, 2009). In his initial announcement on the RepRap.org weblog (Hodgson, 2012: 1-5), Bowyer said a major goal was to put “ideas into the public domain as soon as possible, to ensure that they are unpatentable”; he sought contributions that were free both in price “as well as in freedom”, a nod to the free software ideology of Stallman (2002).

To enable hobbyist participation, a major goal was to be able to use the printer to replicate the printer to make other printers, and the first such copy was made in 2008. The RepRap thus appealed to do-it-yourself hobbyists, variously referred to as “DIY”, “makers” or hardware “hackers”.[6] Bowyer formed an online community to develop and refine the hardware designs using the RepRap.org website. The community leveraged a variety of open source software and hardware tools. This included Arduino, an open source hardware microcontroller with custom open source software libraries that were used to create computer-controlled DIY devices.

Over its first five years, the RepRap Project focused on two of the reverse salients for consumer adoption of 3DP, reducing cost and improving performance of the open hardware design. Consistent with other user communities (cf. Lakhani & von Hippel, 2003), it also allowed users to share knowledge about 3DP usage, beyond designing improvements to the RepRap open hardware. In particular, community members identified possible sources of open source and other free[7] 3D design software that would replace the $1000+ CAD packages used by industrial designers and engineers (cf. Hodgson, 2012).

As with open source software (cf. Rossi, 2006), the open source hardware community of user-innovators focused on “scratching an itch”, i.e. eliminating barriers to their own use of a 3DP system. As with OSS, they spent less time addressing problems that impacted ordinary consumers: in particular, hobbyists had a higher tolerance for ease of use problems (of the hardware, applications and entire system) than would the average consumer.

Also in parallel to open source software (cf. Dahlander, 2007), the availability of open hardware enabled entry by firms. Many utilized the RepRap technology to create other consumer-oriented products, competing with each other and the RepRap open hardware: Bowyer

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6 The maker movement was organized through *Make*, a magazine first published in 2005 by O’Reilly Media, a San Francisco Bay Area company that published numerous books on open source software.

7 Community members emphasized software that used both open source licensing and community production processes (cf. West & O’Mahony, 2008). However, 3DP hobbyists also used limited-functionality versions of proprietary software provided free by commercial software companies such as Autocad and Google (*Make*, 2013).

himself founded one such company, UK-based RepRap Professional. Other what they learned from the RepRap project to create their own technology, as did the founders of Ultimaker. Many of these companies had the cost of goods for heir initial production runs crowdfunded by fundraising campaigns on Kickstarter (Formlabs) or Indiegogo (RepRap Pro).

One of the earliest and most successful consumer 3DP companies was MakerBot Industries, which in 2009 offered began to offer for sale a series of consumer-oriented printers. The company also controlled Thingiverse, an online community to distribute free user-contributed digital designs that could be produced using its printers. Together with its own custom software, the company was perhaps the earliest to offer an end-to-end system for hobbyists and other consumer users. By the end of 2013, it had sold 44,000 printers and had grown to 450 employees worldwide (Biggs & Kumparak, 2014).

4. MakerBot

In January 2009, MakerBot Industries, LLC was founded in Brooklyn by Adam Mayer, Bre Prettis, and Zachary "Hoeken" Smith. The three were active members of NYC Resistor — a "hackerspace" for the New York City DIY community. Smith was also active in the RepRap online community, having started a nonprofit to support the community efforts. Prettis became the CEO, Smith focused on hardware and Mayer on software.

MakerBot developed a series of printers based on both the RepRap printer design and RepRap-compatible object designs distributed via Thingiverse. From its open design roots, the company adopted an increasingly proprietary strategy to differentiate itself from the RepRap open hardware and other consumer-oriented 3D printer companies, including those also derived from the RepRap platform. This included both proprietary hardware components to improve the performance of its printers, and new proprietary software applications to improve the overall ease of use of its system.

In August 2011, the company received $10 million in Series A venture funding,[8] but soon after both Mayer and Smith left the company. In August 2013, MakerBot was acquired for more than $450 million by Stratasys, a Minneapolis-based makers of industrial 3D printers.[9] The respective company CEOs vowed that MakerBot would continue to be run as a separate division.

4.1 Hardware: From Open to Closed Hardware

During its four-year independent existence, the firm delivered five consumer-oriented printers. All were intended to be controlled by personal computers, derived from the RepRap designs, and (like RepRap) used the FDM approach of melting a plastic filament from a spool.

Only two months after they launched their company, the founders used the annual South by Southwest (SXSW) conference in Austin to unveil their first product. The Cupcake CNC was a $750 kit to assemble a 3D printer. The design was based on the RepRap open hardware design, but moved the base rather than the printing head to reduce complexity and weight. MakerBot shipped its first batch of 20 orders in April 2009, and by the end of the year, increased its monthly production batch to 150 units per month (Stern, 2010).

Insert Table 3 about here

8 By comparison, in Fall 2012, Formlabs received $2.9 million from 2,068 backers in one of the most successful crowdfunding campaigns in Kickstarter history; after MakerBot was acquired, in 2013 it received $19 million in Series A funding.

9 The 4.7 million Stratasys shares offered for MakerBot were valued at $403 million when the deal was announced on June 19, but were worth $455 million when the acquisition completed on August 15. The purchase also included an additional 50% stock dividend incentive based on performance through the end of 2014 (Stratays, 2013). By comparison, the 1994 Stratasys IPO raised less than $6 million.

MakerBot built its hardware based on Arduino, an open source electronics controller platform. It made the design of its first printer publicly available using the same free software license (the GNU General Public License) as used by RepRap. The GPL meant that all hacker changes had to be shared back with MakerBot. The same license was also used with its second product, the Thing-O-Matic, which was released the following year in both kit and assembled form. In an interview, Pettis cited the benefits it gained from open hardware designs:

> Because we're open source and the community is so smart, we've seen a lot of participation in the research and development sector. For example, MakerBot Operator Tim Myrtle ripped the guts out of our temperature control code and replaced that section of code with some serious PID math which made the temperature of the nozzle much more stable. Because we're open source, our users know that the code and designs are theirs to hack on. They also know that if they improve their machine, they can share their improvement and everyone in the community benefits (Peels, 2010).

Endorsing this open approach, Pettis criticized an entrepreneurial hardware designer who was selling a derivative of MakerBot's RepRap board without sharing her changes:

> Open Source Hardware is hardware that has an open license. You can copy it, develop it, and even sell it yourself. You must provide attribution to the designer and you must also release the derivative source files under the same license.…
>
> Sometimes an individual or a company makes a derivative of an open source project, goes to market with it and then doesn't share their derivative designs with their changes. This is not only against the license, but it's also not ethical. It is a dead end for the innovation and development which is the heart of the open source hardware community.
>
> …

> At MakerBot, we take open source seriously. It's a way of life for us. We share our design files when we release a project because we know that it's important for our users to know that a MakerBot is not a black box. …When people take designs that are open and they close them, they are creating a dead end where people will not be able to understand their machines and they will not be able to develop on them (Pettis 2010).

In January 2012, MakerBot made several major changes in its product strategy with the first of its Replicator products, named for the ubiquitous fabrication device from the Star Trek television show. The new products provided triple the build volume (from 1500cc to 4900cc). While the product design was publicly available, the design was provided under a Creative Commons license, a less restrictive license. With the Replicator, MakerBot stopped selling printer kits, and only offered assembled products. It also emphasized ease of use and reliability. The Replicator models also offered enclosed cases that reduced the risk of having the printer caught while printing. These attributes supported the company's stated "mission to bring MakerBots to the desktops of everyone" (Bilton, 2012).

However, the greatest change came in September 2012, with the Replicator 2. Unlike the previous products, the design of the Replicator 2 (and all subsequent printers) remained a trade secret, just as the design of other commercial 3D printers was a trade secret. Pettis was quoted as saying

> For the Replicator 2, we will not share the way the physical machine is designed or our GUI because we don't think carbon-copy cloning is acceptable and carbon-copy clones undermine our ability to pay people to do development (Brown, 2012).

The "cloning" was a reference to TangiBot, a (legal) direct copy of the Replicator announced several months earlier to be sold for $1200 (one third less than the Replicator) through manufacturing in China. The designer of the TangiBot sought $500,000 in crowdfunding to launch his company, but the effort failed due to resistance from members of the 3DP and open hardware communities.

Despite this provocation, MakerBot's decision to switch from being a pioneer of open source hardware to a closed source design raised considerable controversy. This included a blistering attack from co-founder Smith, who had been forced out earlier in the year:

> For me, personally, I look at a move to closed source as the ultimate betrayal. … Moving from an open model to a closed model is contrary to everything that I stand for, and as a co-founder of MakerBot Industries, it makes me ashamed to have my name associated with it (Smith, 2012).

In a subsequent blog posting, Pettis questioned the viability of the open hardware model for larger companies:

> I wish there were more examples of large, successful open hardware companies. … There are no models or companies that I know of that have more than 150 employees that are more open. … We are experimenting so that we can be as open as possible and still have a business at the end of the day. … I don't plan on letting the vulnerabilities of being open hardware destroy what we've created. …
>
> This isn't the first change we've made to become more of a professional business, and it won't be our last (Pettis, 2012).

Meanwhile, after its acquisition by Stratasys in 2013, MakerBot also benefitted from its parent company's extensive patent portfolio. After it announced three new printers in early 2014, MakerBot published on its website a list of five patents that it asserted covered its five most recent printers: four of these were Stratasys utility patents, and one was a MakerBot design patent (Table 5). One Stratasys patent (6,004,124) was among four listed in a patent infringement lawsuit filed in November 2013 by Stratasys against Afinia, the importer of a low-cost Chinese FDM printer that competed with MakerBot's products (cf. Weinberg, 2013).

4.2 Software: From Open Source to Proprietary

Over its four-year independent existence, MakerBot evolved its software strategy — as with its hardware design, from a primarily open to partly closed strategy (Table 6).

Its first printer, the Cupcake CNC, used both existing and new open source software for modeling and design. This included Sanguino, an open hardware fork of the Arduino project by Smith originally developed for the RepRap hardware, that used Arduino's open source software libraries for communicating between the computer and the Sanguino microcontroller board. Smith and Mayer incorporated the Arduino software in ReplicatorG, a new open source software application that was the driver for CupCake (and later Thing-O-Matic) printers. The company also used skeinforge, an open source program popular with RepRap users that converted 3D designs into layers that could be printed.

With the 2012 release of its first Replicator printer, the company introduced its own proprietary MakerWare software. Replacing two existing open source packages, the proprietary software served two purposes. First, it allowed the company to correct some of the problems that the open source software had in rendering designs, improving output quality. Second, the new software simplified the process of producing output, improving ease of use.

While MakerBot continued to recommend open source modeling applications, the company made ongoing improvements in its MakerWare software. Unlike earlier open source software, these improvements were not available to open source hobbyists (e.g. members of the RepRap

Project) or to proprietary rivals. At an open hardware conference (2012), Pettis justified its newly proprietary software strategy to maintain a competitive advantage in ease of use:

> We're also not sharing the GUI of MakerBot MakerWare, which is the software that runs it. That's just because we want to have a chance to control the look and the feel and the experience of the user. And these things are really valuable to people who wanna clone us and just make, like, carbon-copy clones, and we're not…and we're not into that. But, it's still hackable, still modifiable (Ragan, 2012).

5. Creating and Leveraging Thingiverse

5.1 Launching the Community

Smith and Pettis started Thingiverse in October 2008 to encourage open sharing of digital designs for physical products. As Smith explained in his announcement on the official RepRap blog:

> One of the most frequent questions I get after people understand what a RepRap does, is a variant of either 'Why do you need a machine like this?' or 'What do you make once you have one?'. Well, Thingiverse.com is an answer to that. This is no ordinary object sharing website. Thingiverse.com is a home for all your digital designs. If you can represent a physical object digitally, then we want it on Thingiverse. (Smith, 2008).

As Pettis explained in a 2010 interview

> We built Thingiverse because we needed a place to share our designs so we wouldn't lose them and so our friends could make what we had made and then modify those designs and make them better. The community is amazing and supportive, and it's also a lot of fun. There is no other place that you can share a design for a physical thing and people around the world will make their own copies within minutes … It's that kind of

> sharing magic that makes Thingiverse the closest thing to teleportation that we've got in this solar system. (Peels, 2010).

While initial uploads were primarily vector drawings for 2D laser cutters, the user-generated content rapidly expanded to include 3D models, electronics, and designs, in a range of 2D and 3D object file formats. Content created by an individual "object designer" was shared freely for other community members to download. This community created the first open repository for digital 3D designs. The design files were free, but the printers cost money, following a common slogan among open source hardware businesses: bits are free, atoms cost money.

Because most 3D designs at the time were offered for sale, the community rules were intentionally designed to encourage sharing and thus increase the value of using the open RepRap hardware (Smith, 2011). This included using the Creative Commons and open source software licenses utilized by RepRap and other open source hardware and software projects, to encourage free revealing and reduce the friction of transaction costs (cf. Harhoff et al., 2003; Balka et al., 2009).

5.2 Structuring Community Participation

In its first five years, the community attracted more than 100,000 3D designs donated by community members. Reasons for this success include pent-up interest in 3DP, global online availability, and its first mover status as an open repository. However, a key aspect of the success of Thingiverse was due to deliberate choices to promote sharing, including motivating contributions and enabling cumulative innovation.

While rights to donated designs rested with the designer, Thingiverse encouraged contributors to utilize one of the well-known Creative Commons licenses. Most of these licenses allowed other community members to create derivative works. One popular license (Creative

Commons - Attribution - Share Alike) required (as with the open source GPL license) that required those making modifications must share back their changes with other community members. This approach facilitated learning and modification, and served to bind the community of users further through nurturing reciprocity among designers. Developing such norms of reciprocity proved an open factor in motivating contributions to free software communities (O'Mahony, 2003).

Another key institutional choice by the community's founders was to emphasize attribution of design works, providing for recognition for designers. Even after MakerBot shifted from open to closed hardware — and moved to assert tighter control over the operation of the Thingiverse website — Pettis emphasized the company's commitment to designer attribution: "The legal terms of use are there to keep Thingiverse legit and protected, not to take away attribution. We know attribution is critical in a community of sharing" (Pettis, 2012).

Attribution facilitates the growth of the community. Thingiverse has grown and evolved into much more than an Open Source and Innovation Sharing platform, but also into the biggest 3D learning community in the digital world (Baichal, 2008). With more than 100,000 designs and more than 21 million downloads by June 2013, Thingiverse experienced an "explosion of uploaded and published 3D designs" (Howard, 2013), fulfilling its founders' vision of creating a universe of things. At the end of 2013, the most downloaded objects included decorative objects, toys, small useful objects (such as iPhone cases), and component designs (such as circuit boards or robot arms) intended for other makers.

5.3 Benefits to MakerBot

MakerBot focused on two distinct user audiences. One were the makers who assembled (and modified) MakerBot kits, using them to print physical objects. The others were fabbers (fabricators) who use code (rather than manual drawing) to describe designs. Most of the fabbers have their attention to the procedural designs, and release their design files in the form of openSCAD files, which are intended to facilitate learning and feedback. In an interview, hobbyist design engineer Syvvich described the function of openSCAD as follows:

> Where you don't design the parts, but you write software and it draws them, which is very cool because you can give various characteristics and every time you need a different gear, you just change the software for your parameters, so the 3D printed clock is one big computer program-a great way to work.

Syvvich is a typical hobbyist whose interest is primarily about using code to express design, but seldom 3D prints his designs. The differences between fabbers and makers was starkly illustrated by the differences in their reaction to MakerBot's decision with the Replicator 2 to shift to a closed (i.e. proprietary) hardware design. Steeped in the ethos of open source software, many of the makers criticized the shift away from open IP policies. Makers who are also fabbers are a minority, although some pulled their designs from Thingiverse to protest MakerBot's new IP strategy.

In contrast to the makers, fabbers are more sympathetic and welcome the trade-off between having a better set of tools for design and the tools becoming closed source, as this Thingiverse community member wrote:

> As a professional graphic artist and computer animator, if I was required to use only open-source software and tools to keep a "Fully-Open title" I would go insane. I would be anchored to the sophistication of the tools and I can tell you, while they are excellent tools and are getting better all the time there is a lot of proprietary technology that is nearly essential to functioning in this industry.… Most people who use 3d printers

> professionally couldn't care less how it works but THAT it works and right now, the challenges of staying "Open" and being competitive in the marketplace are unimaginably difficult for this [open source hardware] business model.[10]

The segmentation of the installed base of Thingiverse users underlines the challenges of mixing open and closed strategies for hardware, software and content, dividing the opinions of contributors, users and investors. In response to the maker community claiming he had violated the GPL by closed sourcing the hardware, Pettis wrote

> It's important to me that we are not violating the licenses of the software. In regards to VC funds, MakerBot does have a duty to do its best to create value for its shareholders, that's part of startup life. But it's not just the VCs, angel, and seed investors, it's also the employees of MakerBot that get value from the company. I'll be the first to say that hardware, open source, and investment are a messy bunch of ingredients to stir up, but we're going to do our best to make it work (Pettis, 2012).

While the closed approach may have deterred contributions to the software and firmware that MakerBot used for its 3DP, it appears to have had limited impact on Thingiverse. Most of the design activities and the sharing of design files remain unaffected, as design files in the Thingiverse are primarily code base subject to the protection of copyright. The attribution system works with fabbers as in the way meritocracy works in other open source software communities.

Thingiverse still remains as the largest repository for 3D designs, with copyright and attribution used to bind user commitment to ongoing sharing and modification of each others' designs. Thingiverse forms an important bridge for the transition between the digital to the

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[10] Comment appended to Pettis (2012) by user Erik J. Durwood II, September 23, 2012.

physical worlds, and with freely available designs induces not only an increase in sales of 3D printers, but also the growth of materials. It also remains an online platform for open design, despite the seeming divergence with MakerBot's IP strategy with its shift from open to closed design.

6. Discussion

The 3D printing industry began with a fragmentation of firms and technologies, protected by traditional patent-based IP strategies. Consumer adoption was delayed until an open hardware community — with shared IP — democratized access to the technology by both users and entrepreneurial startups. One company, MakerBot Industries, utilized a combination of open and proprietary strategies to address the barriers to consumer adoption.

We believe MakerBot's use of the Thingiverse content community and its shift from an open to more closed offers implications in three areas: the future adoption of 3D printing, the similarities (and differences) between open software and open hardware, and the firm sponsorship of user communities.

6.1 The Future of 3D Printing

The adoption of 3DP has important similarities and differences to the pattern of personal computing 30 years earlier. As such, we can offer some observations about the path of its future adoption (and of technology adoption more generally).

The adaptation of 3DP for personal use depended on various technologies developed for more expensive industrial use, including the availability of an industrial 3D printer used while the first open source RepRap 3D printer was being developed. This parallels the PC era, when Bill Gates developed Microsoft's first software using Harvard's mainframe computer (Wallace & Erickson, 1992), and also the Linux open source community, which was modeled on Minix, a personal computer implementation of the mainframe Unix operating system (Moody, 2001). In a similar way, MakerBot's decision to target the consumer (rather than hobbyist) market paralleled that of Apple Computer. By shifting from a kit to a preassembled printer with a nice case, Pettis emulated the earlier decision of Steve Jobs with the Apple II (Moritz, 1984).

Similarly, the use cases for the first generation of consumer 3D printers are in as many ways as fanciful for first generation PCs, with printing desktop trinkets in the 2010s the equivalent of storing recipes in the 1970s. As with personal computers, professionals (such as designers or engineers) who want a home device have a reason to buy hardware but the average consumer does not. Also as with computing, there are a large number of small and medium-sized business (SMB) whose needs could potentially be met with consumer-priced offerings. And as with copiers, scanners and MP3 files, there are unresolved IP issues of fairly balancing the rights of creators and users.

Finally, as with early PCs, the technical limitations of the hardware mean that consumer products are toys that are years away from supplanting industrial equipment. For 3DP, that includes both the limitations of the products (in terms of speed, resolution, output quality and output durability), but also the limitations of the remainder of the system (including ease of use and content). As with other technologies that start with lower performance, 3DP is expected to disrupt established business models (Anderson & Sherman, 2007), but such widespread impacts are years off. In the meantime, service bureaus (such as Shapeways) will allow SMBs and individuals to have access to higher-quality output at a reasonable price.

If these technical problems can be solved at a pace comparable to Moore's Law, then 3DP has several key advantages that could make its adoption more rapid than personal computing. First, it has the widespread adoption of personal computing hardware and software. Unlike the first 20 years of personal computing, it also has the Internet as a mechanism for communicating and sharing content. Perhaps most importantly, it has proven institutional innovations — such as user communities and open source licenses — that can facilitate the rapid dissemination of both 3DP technology and content.

By this analogy, a possible risk for 3DP is the mismatch of industrial- and consumer-focused business models, consistent with Moore (2005: 29-48). High-margin, high-service computing companies such as IBM and Cisco divested high-volume (but low-margin) consumer businesses, raising the question whether the business models of MakerBot and its parent Stratasys will be compatible in the long run.

6.2 Implications for Open Source Hardware

Open source software has enabled the entry of numerous startup companies (cf. Dahlander, 2007). However, only a handful of companies have succeeded based on fully open designs: instead, companies have chosen to either keep parts of their technology closed, or restrict access to their communities (West, 2003; Shah, 2006; West & O'Mahony, 2008).

Open source hardware has many of the same implications for firms as open source software, but questions remain as the former is both a less common phenomenon and less often studied. These questions include both the viability of open hardware business models, and also the ability of firms (or communities) to tightly regulate IP access to support those business models.

The cost of producing physical goods led Raasch et al (2009) to conclude that open design communities needed a commercial company to fund and organize activities that the community could not, and such companies needed to have partly closed strategies to make those activities profitable. Several years later, MakerBot's CEO claimed that purely open source hardware strategies were not viable, as an (unverifiable) justification for why MakerBot shifted from open to closed source hardware designs.

MakerBot's experience also raises questions about the viability of IP licenses such as the GPL in allocating rights to hardware, including forced sharing and deterring entry. Early on, MakerBot fought to get a RepRap community member to disclose her modifications to a MakerBot design (Pettis, 2010). Despite a GPL license, MakerBot later forked the RepRap's open design as the basis of its proprietary products, while a MakerBot competitor threatened to sell a (legal) clone of one of its open designs.

It is too early to tell how these business model and IP limitations will impact the formation or success of other 3DP companies.

6.3 Implication for User Communities

While enabled by much of the same infrastructure as other online user communities, Thingiverse is, in many ways, a unique kind of community. As a repository for digital designs for tangible objects, it links the world of online (and virtual) collaboration with the distributed production of physical objects — production that, in the future, is made possible by 3D printers.

The Thingiverse community provided complementary goods that increased the value first of the RepRap open hardware products, and then of MakerBot's proprietary products. The emphasis on sharing — rather than sales — parallels communities that openly share complements for video games and sound files (Jeppesen & Molin, 2006; Jeppesen & Frederiksen, 2006) rather than the more familiar app store example (MacMillan et al, 2009).

In shifting from open source hardware and software to proprietary designs, MakerBot was able to build barriers to rivals at the cost of creating tensions with the open design community. However, unlike in open source software communities — where roles are continuously delineated by matters of degree (Crowston & Howison, 2006) — the Thingiverse community had two distinct types of users, with two distinct reactions to MakerBot's partly closed strategy. The limited opposition by both groups suggests that MakerBot is providing the openness that matters to most users — object design — or that users accept the firm's later distinction between open content and closed hardware for manufacturing that content.

The openness of the Thingiverse community raises the question of how long it will continue to provide advantage for its sponsor. As when the community was launched, MakerBot benefits from the growth of demand for 3D printing. At the same time, the wide variety of object designs creates value not only for MakerBot's products, but also for those of its competitors.

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8. Tables

Table 1: Additive manufacturing technologies and patents

Process	First Granted US Patent (Priority Date)	Key Inventor (Employer)	Feedstock
Stereolithography (SLA)	4,575,330 (1984)	Chuck Hill (UVP, later 3D Systems)	Liquid plastic
Laminated Object Modeling (LOM)†	4,752,352 (1986)	Michael Feygin (later Helisys)	Paper
Selective Laser Sintering (SLS)	4,863,539 (1986)	Carl Deckard (U. Texas)	Plastic or metal powder
Solid Ground Curing (SGC)	4,961,154 (1986)	Itzchak Pomerantz (SciTex, later Cubital)	Liquid plastic
Fused Deposition Modeling (FDM)††	5,121,329 (1989)	Scott Crump (Stratasys)	Continuous spool of plastic (later metal)
Electron Beam Melting (EBM)	5,786,562 (1993)	Ralf Larson (Larson Brothers)	Metal powder
Inkjet-based approaches			
Three-Dimensional Printing (3DP)†††	5,204,055 (1989)	Michael Cima, Emanuel Sachs (MIT)	Liquid plastic or plastic-metal
Inkjet Printing (IJP)	5,506,607 (1991)	Royden Sanders Jr. (later Solidscape)	Wax
PolyJet	6,259,962 (1999)	Hanan Gothait (Objet)	Liquid plastic

† Trademark of Helisys
†† Trademark of Stratasys
††† Trademark sought by MIT, later abandoned

Table 2: Key 3D Printing Companies

Founded	Company	Spinoff Parent	HQ	Printing Process	First System	Initial Target	Exit
1985	**Helisys (née Hydronetics)**		Los Angeles	**LOM**	1990	Industrial	1996: IPO 2000: out of business
1986	**3D Systems**	UVP	Los Angeles	**SLA**	1987	Industrial	1987: IPO (Vancouver)
1986	**Cubital, Ltd.**	Scitex	Israel	**SGC**	1991	Industrial	2000: out of business
1987	**DTM Corporation**	UT Austin	Austin	**SLS**	1992	Industrial	2001: Acquired by 3D Systems
1989	**Stratasys**		Minneapolis	**FDM**	1992	Industrial	1994: IPO (NASDAQ)
1993	**Solidscape (née Sanders Prototype)**		New Hampshire	**IJP**	1994	Commercial	2011: Acquired by Stratasys
1994	Z Corp		Boston	3DP	1997	Industrial	2012: Acquired by 3D Systems
1998	**Objet**		Israel	**PolyJet**	2001	Industrial	2012: Merged with Stratasys
1996†	ExOne	Extrude Hone	Pittsburgh	3DP	1999	Industrial	2013: IPO (NASDAQ)
1997	Arcam	Chalmers University	Sweden	EBM*	2002	Industrial	2000: IPO (Nordic Growth Market)
2007††	Shapeways	Phillips	Netherlands	*Service Bureau*	*2008*	Commercial	n/a
2009	Afinia		Minneapolis	FDM	2012	Consumer	n/a
2009	MakerBot		New York City	FDM	2009	Consumer	2013: Acquired by Stratasys
2011	RepRap Professional	RepRap Project	UK	FDM	2011	Consumer	n/a
2011	Ultimaker		Netherlands	FDM	2011	Consumer	n/a
2011	Formlabs		Boston	SLA	2012	Consumer	n/a

Processes invented by a company founder or employee are listed in **bold**
* Exclusive patent license from inventor
† Parent company began 3D printing in 1996, spun off in 2005
†† Spun off as independent company in 2010

Table 3: Potential barriers to consumer adoption of 3D printing

Category	Attributes
Printer performance	Speed, quality, output size, output durability
Cost	Initial cost, cost of consumables
Computer performance	CPU cycles, RAM, hard disk
Application software	Computer Aided Design (CAD) applications
Ease of use	Graphical interfaces, hardware operation, integration
Content (digital designs)	Self-designed, standardized components, community donated content

Table 4: MakerBot product history, 2009-2013

Date	Product	Price§	Design License	Build Volume	Min. Layer Resolution	Printing Material
March 2009	Cupcake CNC	\$750†	GNU GPL	100 x 100 x 150 mm	n.s.	PLA (Polylactic Acid)
Sept. 2010	Thing-O-Matic	\$1,300† \$2,500	GNU GPL	110 x 110 x 120 mm	0.25 mm	PLA
Jan. 2012	Replicator	\$1,750	Creative Commons	225 x 145 x 150 mm	0.20 mm	PLA or Acrylonitrile Butadiene Styrene (ABS)
Sept. 2012	Replicator 2	\$2,200	*trade secret*	285 x 153 x 155 mm	0.10 mm	PLA
Jan. 2013	Replicator 2X	\$2,800	*trade secret*	246 x 163 x 155 mm	0.10 mm	PLA or ABS
Jan. 2014	Replicator Mini*	\$1,380	*trade secret*	100 x 100 x 125 mm	0.20 mm	PLA
Jan. 2014	Replicator (5th generation)*	\$2,900	*trade secret*	252 x 199 x 150 mm	0.10 mm	PLA
Jan. 2014	Replicator Z18*	\$6,500	*trade secret*	305 x 305 x 457 mm	0.10 mm	PLA

Source: MakerBot website, news reports
§ Base model at time of introduction
† Kit form
* Introduced after being acquired by Stratasys

Table 5: Self-declared patents applicable to MakerBot products

Patent	Priority Date	Issue Date	Assignee	Applicable Products
6,004,124	1/26/98	12/21/99	Stratasys	Replicator 2,2X,Mini, Z18, 5th gen
6,722,872	6/23/99	4/20/04	Stratasys	Replicator Z18
6,749,414	4/30/01	6/15/04	Stratasys	Replicator 2X
7,384,255	7/1/05	6/10/08	Stratasys	Replicator 2,2X,Mini, Z18, 5th gen
D677,723	9/18/12	3/12/13	MakerBot	Replicator 2,2X

Source: www.MakerBot.com/patents; also US PTO

Table 6: Commercial and open source software for consumer 3D printing

Category	Input	Output	Open Source Examples	Commercial Examples
Modeler	Drawing file (.dwg, .dxf), wavefront file (.obj)	Stereo lithography file (.STL)	Blender, OpenSCAD, Art of Illusion	Google Sketchup, Autodesk 123D Design
Slicer	STL file	Layer definition (G-Code) file	skeinforge, Slic3r	MakerWare, KISSlicer
Printer Driver	G-Code file	Printer commands	ReplicatorG	MakerWare
Controller Driver Library	*Programmer APIs*	*Low-level serial output*	Arduino, Sanguino	

Source: project websites, *Make* (2013)

***Biographical Note**

Joel West is a professor of innovation and entrepreneurship at the Keck Graduate Institute of Applied Life Sciences, one of the seven Claremont Colleges. His research examines the strategic use of openness in areas such as open innovation, open source software, and open standards. He is the author of the OpenInnovation.net weblog and co-editor of two books on open innovation.

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