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3D printing and the intellectual property system

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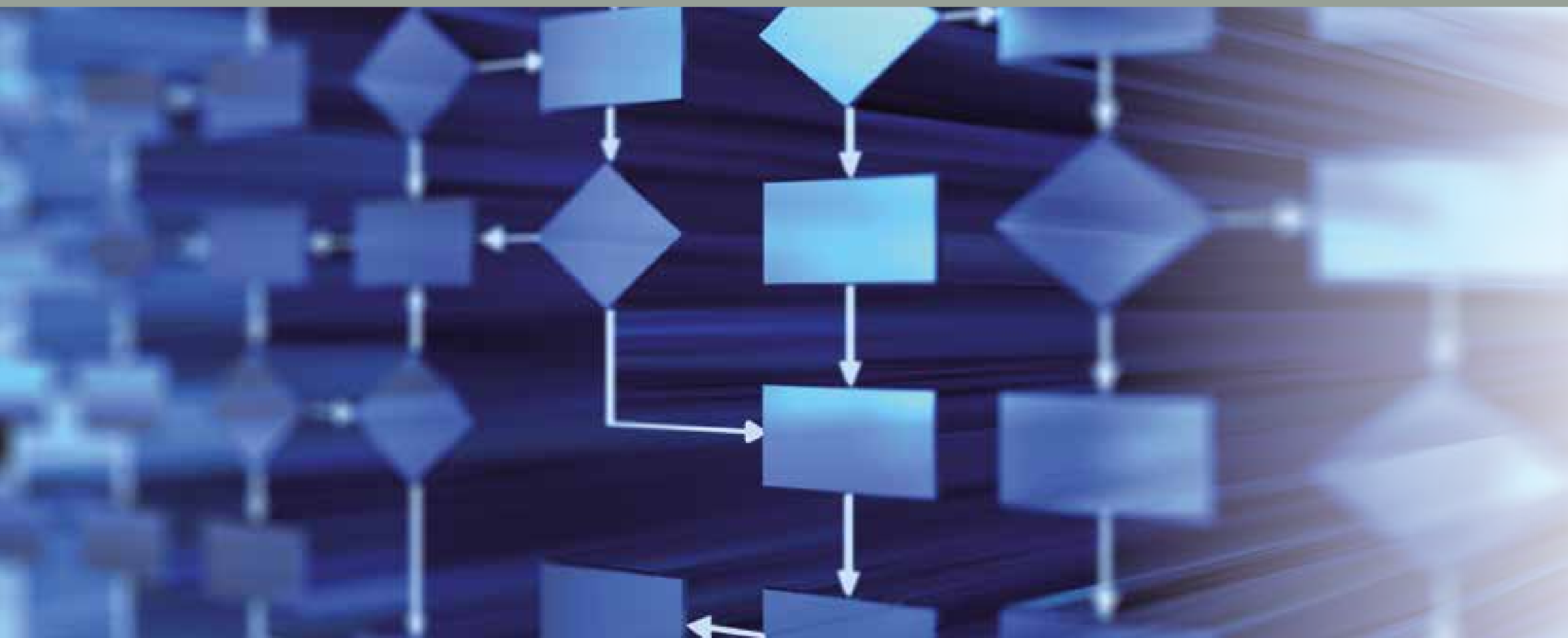

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3D Printing and the Intellectual Property System

Stefan Bechtold*

Abstract:

Three-dimensional (3D) printing – or "additive manufacturing" – technologies differ from traditional molding and casting manufacturing processes in that they build 3D objects by successively creating layers of material on top of each other. Rooted in manufacturing research of the 1980s, 3D printing has evolved into a broad set of technologies that could fundamentally alter production processes in a wide set of technology areas. This report investigates, from the perspective of an intellectual property scholar, how 3D printing technology has developed over the last few decades, how intellectual property rights have shaped this breakthrough innovation and how 3D printing technologies could challenge the intellectual property rights system in the future.

As in other areas of innovation policy, the role of the intellectual property system in fostering innovation in 3D printing technologies is a complex one. It played a beneficial role in some instances (sometimes intended and sometimes unintended), and it may have played a neutral or detrimental role in other instances. Studying the progress of 3D printing technologies thereby also informs us about the intricate relationship between intellectual property and innovation.

Keywords: Innovation, 3D printing, intellectual property

JEL Codes: K29, L60, O30, O32, O34, O38

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Introduction

Three-dimensional (3D) printing technologies have attracted considerably media attention over the last few years. Some of the attention may be the result of a media hype. However, there are aspects of 3D printing – or, more accurately, "additive manufacturing" – technologies which could have a transformative impact not only across a large number of different industries, but also on how products in general are produced, distributed and consumed.

It is important to understand how this technology came into place, how it developed over time and what kind of innovation ecosystem it produced. It is even more important for innovation policy research to analyze how this development interacted with legal and societal institutions whose goal is to foster innovation. Ideally, such insights can inform the policy discourse on how to design innovation policies for 3D printing and other potential breakthrough innovations.

This report investigates, from the perspective of an intellectual property scholar, how 3D printing technologies have developed over the last few decades, how intellectual property rights have shaped this breakthrough innovation and how 3D printing technologies could challenge the intellectual property rights system in the future. The report is based on an analysis of technological developments, the existing marketplace for 3D printing and the relevant innovation policy literature on this technology.

The report proceeds as follows. Section II provides an overview of the development of 3D printing technology and describes the potential of the technology to transform economic activity in a multitude of markets. Section III describes important players in the innovation ecosystem for 3D printing technologies and demonstrates how changes in technology and patent protection affected this ecosystem. Section IV describes the impact of the intellectual property system on the evolvement of 3D printing technologies in more detail. Section V concludes this report.

Development of 3D Printing Technology

1. Technology

The term "3D printing" relates to a set of technologies which follow an approach towards manufacturing processes that is fundamentally different from traditional approaches. With traditional molding or casting manufacturing processes, objects are created by either molding material or subtracting material from a raw object. The typical production process involves casting, fabricating, stamping and machining. With 3D printing technologies, objects are built by successively creating layers of material on top of each other.

A typical 3D printing process starts with either a 3D scan of a real-world object, or with the creation of a digital representation of such object in a "computer aided design" (CAD) software package. The shape and other characteristics of the object are then stored in specialized file formats. After fixing potential errors in the digital representation of the object, specialized software transforms the representation into sliced instructions for a 3D printer, which then creates a three-dimensional reproduction of the original object. Once the actual printing is done, high-resolution post-processing techniques are often applied, either compensating shortcomings of the 3D printing process or increasing the quality or resolution of the produced object. As there are no limitations in the digital representation of real-world objects, at least conceptually, nearly any shape or geometry can be reproduced with a 3D printer.

A large variety of 3D printing processes exist today. The main difference lies in the way these processes deposit layers of raw material and in the kinds of raw material the processes are able to use. Concerning the way 3D printing processes deposit layers of raw material,

> **3D Printing: Terminology**
>
> While the term "3D printing" has gained much popularity in recent years, the more accurate term for the broad set of technologies of interest is "additive manufacturing." In a narrow sense, 3D printing refers to processes that extend normal inkjet printing technology into the third dimension by sequentially depositing material onto a powder bed with a standard or custom-made inkjet print head. However, the term is also used nowadays to describe the broader set of technologies which all have in common that they create 3D objects by laying material on top of each other in layers. This report will follow a general trend and use the terms "3D printing" and "additive manufacturing" interchangeably.

the technologies can be categorized as follows (see ASTM International 2012; Wohlers Associates 2014, pp. 28-39; Bechthold, Fischer et al. 2015, pp. 10-12):

- In *material extrusion* processes, material is selectively dispensed through a nozzle or orifice. An important example is fused deposition modeling, in which a heated nozzle ejects small beads of plastic resin, wax or another material which hardens immediately.
- In *material jetting* processes, droplets of build material are selectively deposited.
- In *binder jetting* processes, an inkjet print head disperses glue to locally bind powder material. This process, which was originally developed by MIT, works similarly to normal inkjet printers, in that it dispenses material through an inkjet print head.
- In *sheet lamination* processes, sheets of material are bound together to form an object. In laminated object manufacturing, for example, sheets of paper, plastic or metal are subsequently laid on top of each other, with a laser cutting the outline of the object on each layer.
- In *vat photopolymerization* techniques, a liquid photopolymer is solidified by a controlled light source. With stereolithography, for example, the photopolymer is exposed to an ultraviolet laser. The light source hardens the exposed regions of the polymer. This process is repeated layer by layer until the object is finished.
- In *powder bed fusion* techniques, thermal energy selectively fuses regions of a powder bed. The powder raw material is then melted layer by layer. In selective laser sintering, for example, a laser beam is applied to a layer of powder which is deposited on a build platform. The laser sinters the material into the right shape. Thereafter, the build platform moves down, and the laser draws the next layer.
- In *direct energy deposition* techniques, thermal energy is used to fuse materials by melting as the material is being deposited.

The raw material which 3D printing processes may use to create 3D objects varies greatly from technology to technology. Typical materials include thermoplastics, modeling clay, ceramic materials, metal alloys, glass, paper, photopolymers, and even living cells and food. The material comes in the form of powders, filaments, liquids or sheets. While some material (thermoplastics) can be melted and remelted several times, others (e.g. thermosetting polymers) cannot be melted back into a reusable liquid form as their internal composition changes once they are melted (Bechthold, Fischer et al. 2015, p. 13).

The current and potential applications of 3D printing technologies are diverse. The main application of 3D printing technologies was originally “rapid prototyping.” Engineering and industrial design companies have been using 3D printing since the 1980s in order to accelerate their design and prototyping processes. Increasingly, however, 3D printing has also been used to produce components or even finished products. Currently, large-scale 3D printers are used to print parts of buildings, cars, aircraft, electric motors and generators. Typical industry sectors in which 3D printers are used include construction, industrial design, automobile, aviation, aerospace and military sectors. As 3D printing allows the production of a small number of goods at low costs, this technology is very attractive to industries with small series production, such as the aviation and aerospace industries (Bechthold, Fischer et al. 2015, p. 67). But 3D printers are also used in the medical sector to produce, for example, custom-made sockets for hip replacements and hearing aid shells (Bechthold, Fischer et al. 2015, pp. 29-35; Lipson and Kurman 2013, pp. 105-138; Li 2014).

In addition, end consumer products can be produced with 3D printing technologies. This includes fashion, footwear, jewelry, glasses and even food (Li et al. 2014). As these examples demonstrate, the size of printable objects depends on the kind of 3D printer used; it can range from millimeters to several meters or even larger objects.

2. Historical Development

While 3D printing has received attention from the wider public over only the last few years, its technological roots date back several decades (for 19th century examples of photosculpture and topography, see Bechthold, Fischer et al. 2015, p. 6). In the late 1970s, Wyn Swainson from Denmark received a patent on a technology using two laser beams to create 3D objects (U.S. Patent no. 4,041,476, issued Aug. 9, 1977). Other inventors explored the use of layered molding processes to create such objects (e.g. U.S. Patent no. 4,247,508, issued Jan. 27, 1981).

In the 1980s, R&D activities concerning 3D printing technologies intensified considerably. In 1981, Hideo Kadama of the Japanese Nagoya Municipal Industrial Research Institute presented a method to create 3D plastic models by exposing liquid photo-hardening polymer to ultraviolet rays (Kodama 1981). In 1984, Chuck Hull applied for a patent on a prototype system based on stereolithography, which was described above (U.S. Patent no 4,575,330, issued Mar. 11, 1986).

In 1986, Chuck Hull cofounded 3D Systems, which would later became one of the leading companies in the industry. 3D Systems commercialized stereolithography into the first commercial 3D printer in 1988. The company did not only develop the 3D printer itself. It also developed a new file format (STL, STereoLithography) which describes the surface geometry of 3D objects and which has evolved into an industry standard for many decades.

Also in the late 1980s, Scott and Lisa Crump developed the fused deposition modeling technology described above. They received various patents on it (e.g. U.S. Patent no. 5,121,329, issued June 9, 1992; U.S. Patent no. 5,340,433, issued Aug. 23, 1994) and co-founded Stratasys, another important industry player.

In 1986, Carl Deckard filed a patent on selective sintering processes which enabled the use of materials other than polymers (e.g. metals and thermoplastics) for 3D printing purposes (U.S. Patent no. 4,863,538, issued Sept. 5, 1989). The company he founded (Nova Automation, later renamed DTM Corporation) was acquired by 3D Systems in 2001. And in 1987, Michael Feygin filed a patent on sheet lamination in which a laser cuts thin sheets of paper or other material into a desired shape, and then layers of such shapes are added on top of each other (U.S. Patent no. 4,752,352, issued June 21, 1988). The company he founded (Hydronetics) was later renamed to Helisys and Cubic Technologies.

In the 1990s, companies started to use 3D printing technologies for prototyping purposes. In addition, researchers at Stanford and Carnegie Mellon proposed new techniques of additive manufacturing, involving microcasting (Amon, Beuth et al. 1998) and spraying of materials (Beck, Prinz et al. 1992). Starting in 1993, MIT received patents on 3D printing technologies in the narrow sense: this was inspired by inkjet technology used in normal inkjet printers (U.S. Patent no. 5,204,055, issued Apr. 20, 1993; U.S. Patent no. 5,387,380, issued Feb. 7, 1995). MIT later licensed its patents to Z Corporation and a few other companies for the development of 3D printers.

While 3D printing technologies gained wider acceptance in the commercial manufacturing industry in the early 2000s, it became apparent that these technologies could also be used to produce end consumer products. In 2005, Adrian Bowyer started the RepRap project at the University of Bath. Initiated as an open source project to create a 3D printer which can reproduce itself, it has had a considerable impact on the development of low-cost consumer-market 3D printers and a flourishing ecosystem of hardware manufacturers, software programmers and service providers, all focusing on the 3D printing consumer market.

3. Impact

The commercialization of 3D printing technologies has already had a considerable impact on production processes in various industries. It has enabled rapid prototyping in many industries and transformed the production of product components in some industries.

Current Impact of 3D Printing: Data

Estimations for the average current cost of industrial 3D printers range between $75,000 (McKinsey Global Institute 2013, p. 108) and $90,370 (Wohlers Associates 2014, p. 111), although the price for some industrial systems exceeds $1 million. The price for personal 3D printers has plummeted from over $30,000 a few years ago to less than $1,000 (McKinsey Global Institute 2013, p. 109). An estimated $528.8 million was spent on raw material for 3D printers in 2013 (Wohlers Associates 2014, p. 112). The worldwide 3D printing market generated an estimated $3.07 billion in revenues in 2013 (up by 32.7 % from 2012; Wohlers Associates 2014, p. 109).

Forecasts on the potential impact of 3D printing technologies in the future range from cautiously optimistic to enthusiastic. 3D printing technologies could have a profound impact not only on manufacturing processes, but also on supply and distribution chains. They will play an increasingly important role not only in rapid prototyping, but also in the production of product components and finished products (Bechthold, Fischer et al. 2015, pp. 15-17). They may enable mass-scale customization of products, reduce inventory costs and optimize product design. They could also lead to a world of decentralized manufacturing, in which objects are produced close to the customer or, in the extreme, even by the customer himself. A decentralization of the production of physical objects, coupled with the ability of customer-tailored product design, could have a deep impact on traditional production channels.

By disentangling design information about an object from the production of the object, 3D printing technologies share common features with other digital technologies: as the creation of information about an object is separated from the production of the object, old business models become challenged and new business models for both parts of the production process appear on the horizon (Lemley 2015). As a result, 3D printing has the potential to disrupt traditional manufacturing and supply chains, thereby leading to innovation in business models. It could also open access to new financial resources through crowdsourcing, enable efficient targeting of niche markets and integrate consumers into the value chain (Rayna and Striukova 2014, p. 127; Ghilassene 2014, pp. 9-11).

Future Impact of 3D Printing: Data

Industry observers forecast that the 3D printing market will generate revenues of $20 billion by 2020 (Wohlers Associates 2014, p. 116). The impact of the technology is estimated between $230 and $550 billion per year by 2025, with the largest impact being on consumer users ($100 to $300 billion), direct manufacturing ($100 to $200 billion) and the creation of tools and molds ($30 to $50 billion; McKinsey Global Institute 2013, pp. 105, 110).

Whether forecasts on the future impact of 3D printing will materialize will, among other things, depend on whether 3D printing can overcome some of its current technical challenges. The costs of industrial 3D printers is still very high, and the suitable raw material is considerably more expensive than raw material which can be used in traditional manufacturing processes. Furthermore, 3D printing is still a slow process, often requiring many hours or days of printing to finish an object. The future impact of personal 3D printers is also hard to predict. As personal 3D printers are becoming more reliable and their design and marketing are improving considerably, they have the potential to be attractive to consumers, both as far as lifecycle costs (Wittbrodt, Glover et al. 2013) and environmental impact (Kreiger and Pearce 2013; Bechthold, Fischer et al. 2015, pp. 79-84; Lipson and Kurman, pp. 197-215) are concerned. However, it is hard to predict the impact of 3D printing on end consumer markets, as this will depend on the future ease of use, the adoption of the technology beyond enthusiasts and hacker circles, and many other business factors.

3D Printing Innovation Ecosystem

As Section II has shown, 3D printing technology has progressed rapidly to a state where it has not only impacted a great variety of manufacturing industries, but also shows some potential to fundamentally alter mass production processes, supply chains and boundaries between producers and consumers. These technological possibilities have been enabled by a complex web of different players who – directly or indirectly – contributed to the technological advancement of 3D printing. This section will provide an overview of the innovation ecosystem created by 3D printing technology. It will, firstly, focus on the industrial 3D printing sector, followed by a discussion on the emerging market for personal 3D printing products and services.

4. Industrial 3D Printing

The development of 3D printing systems for large-scale industrial applications follows familiar patterns in the manufacturing and related industries. Early inventions concerning 3D printing technologies came from individuals who subsequently created companies to commercialize their inventions, some of them more successfully than others (see supra Section II 2). Currently, about 34 manufacturers produce and sell industrial 3D printing systems. Eighteen of these companies are located in Europe, seven in China, six in the U.S. and two in Japan. Nine of them sold more than 100 systems in 2013 (Wohlers Associates 2014, p. 59). This also indicates that a large proportion of 3D printing companies in many countries are small or medium size enterprises (see Expertenkommission Forschung und Innovation 2015, p. 73).

The 3D printing industry is a research-intensive industry. A survey among 3D printing system manufacturers revealed that average R&D spending was 19.1 % of 2013 revenues (Wohlers Associates 2014, p. 59). The market is dominated by two large system manufacturers: Stratasys (based in Israel and the U.S.) and 3D Systems (based in the U.S.). Other important players include Beijing Tiertime (based in China), EOS and Envisiontec (both based in Germany). The industry has seen a certain degree of consolidation, exemplified by larger acquisitions (e.g. the acquisition of Solidscape by Stratasys in 2011 or of Z Corporation by 3D Systems in 2012).

As the 3D printing industry matured and diversified, standardization of terms, processes, interfaces and manufacturing technologies have become an important issue. The ASTM International Committee F42 on Additive Manufacturing Technologies was formed in January 2009 to address these challenges. It aims at developing consensus standards, thereby facilitating the adoption of 3D printing technologies into various industry sectors. Up to the present day, the committee has finished or is working on numerous standards for testing and evaluation, terminology, and properties of raw materials and processes used in 3D printing.[1] In 2011, ASTM International also adopted a novel standard file format for transferring information between design programs and 3D printing systems. While the de facto industry

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1 See http://www.astm.org/COMMIT/SUBCOMMIT/F42.htm. Until 2001, ASTM International was known as the American Society for Testing and Materials.

standard STL, which has been in use since the 1980s, only enables the representation of information about a surface mesh, the new XML-based file format can also represent information about color, texture, material, substructure and other properties of an object. Participation in the standard setting body is voluntary, and non-members are able to interact with the standardization committee (Lipson and Kurman 2013). Standards are adopted by consensus, but voting privileges are limited to members. Some of ASTM's standards have been developed as joint standards together with the ISO Technical Committee 261 on Additive Manufacturing.

Standardization efforts are not restricted to the United States. In the European Union, the "Support Action for Standardization in Additive Manufacturing" (http://www.sasam.eu) was a project sponsored by the European Commission under its Seventh Framework Program from 2012 to 2014 to coordinate 3D printing standardization activities in Europe. The evolvement of 3D printing technologies has also had an impact on patent classifications. The U.S. Patent and Trademark Office has organized two additive manufacturing summits since 2012, bringing together interested parties from industry, academia and the patent world. In addition, the Cooperative Patent Classification, developed by the European Patent Office and the U.S. Patent and Trademark Office, now includes a special subclass for additive manufacturing and 3D printing in its patent classification (B33Y). This should make it easier to classify this technology in patent applications and to search for prior art in the future.

Funding for 3D printing companies and R&D activities comes from a variety of sources. Venture capital plays a certain role. Both manufacturers of 3D printing equipment and service providers have been successful in raising venture capital. Governments also provide significant funding for 3D printing technologies through various sources. Apart from general research channeled through national science foundations in various countries and the European Union's Seventh Framework Program, targeted government funding goes into 3D printing projects related to energy, military applications and outer space. The U.S. Department of Defense, for example, has been an active supporter of 3D printing research, as have been the U.S. National Laboratories (Wohlers Associates 2014, pp. 207, 209). The U.S. Department of Energy's Advanced Research Project Agency-Energy (ARPA-E) has recently funded a project to produce a 30 kW induction motor using only 3D printing technologies.[2] NASA is investigating the use of 3D printing technologies for the production of replacement parts in outer space missions, and the NASA Langley Research Center has been leading a U.S. government interagency 3D printing working group since 2010 (Wohlers Associates 2014, p. 199).

3D printing is also increasingly the object of large-scale government initiatives. In 2012, for example, the U.S. government proposed a "National Network for Manufacturing Innovation" (NNMI). One of these institutes, "America Makes," focuses on 3D printing technologies. Its goal is to facilitate collaboration among the corporate and academic sector, as well as government agencies, to bring 3D printing technologies into mainstream manufacturing (http://americamakes.us). The institute is a public-private partnership, combining 50 companies, 28 universities and research labs, and 16 other organizations, and has been supported by the U.S. government with $ 50 million (Bechthold, Fischer et al. 2015, p. 59). The European Union has funded 3D printing research with a total budget of € 225 million in its 7th Framework Program (2007-2013) and remains an active supporter in the follow-up "Horizon 2020" program (European Commission 2014). The German government granted about € 21 million in research funding for 3D printing between 2003 and 2013 (Bechthold, Fischer et al. 2015). China has reportedly made heavy strategic investments in 3D printing technologies. In China, government-funded activities are relatively more important than company-driven research and development (Expertenkommission Forschung und Innovation 2015, p. 74).

[2] Leslie Langnau, Will We 3D-Print Electric Motors?, Oct. 6, 2014, http://www.makepartsfast.com/2014/10/7479/3d-print-electric-motor.

3D printing is also an active area of research at many universities worldwide (Wohlers Associates 2014, pp. 213 et seq.). Some universities, in particular MIT and the University of Texas, own considerable patent portfolios on 3D printing technology (see infra Section IV 1 a). As in other technology areas, 3D printing research and development has taken place both in companies and at universities. Nevertheless, with perhaps the exception of MIT and the licensing of its 3D printing patents, many commercially viable 3D printing patents seem to have emerged from the commercial sector. Key engineering personnel of important 3D printer manufacturers filed many of the early 3D printing patents, and 3D printing manufacturers are investing substantial amounts in their R&D activities. In the future, basic science research that is most relevant to 3D printing may occur in the development of new or refined 3D printing processes, or in the development of new raw materials for printing.

Looking at the development of 3D printing technologies in the commercial sector, it is interesting that many of the technological breakthroughs were achieved by start-up companies, rather than large established printing or engineering companies. Hewlett Packard entered into a short-lived agreement with Stratasys in 2010, according to which Stratasys would manufacture HP-branded 3D printers. The agreement was dissolved in 2012 (Wohlers Associates 2014, p. 130). In late 2014, HP announced it would enter the industrial 3D printing market in 2016. Regardless of HP's technology and marketing capabilities, the company which once dominated the printer market is a latecomer to the 3D printing market. Similarly, the German Trumpf Group, a world leader in sheet metal fabrication machinery and industrial lasers, became active in 3D printing technologies in 2000, but stopped its activities a few years later. In 2014, the company re-entered the market by creating a joint venture with an Italian producer of high-precision laser machinery (Expertenkommission Forschung und Innovation 2015, p. 74 note 266).

These two examples may echo a general observation that, in many industries, real breakthroughs often come from new entrants into the industry, rather than industry incumbents. For new entrants, patent protection may play an important role in order to protect themselves against industry incumbents and to signal to potential investors that they have a sound technology base to offer (Long 2006).

5. Personal 3D Printing

In addition to the industrial 3D printing sector, a vibrant market for 3D printing systems and services which are targeted towards the end consumer has developed over the last few years. This has led to an innovation ecosystem of its own. It consists of open source enthusiasts, hardware manufacturers, software programmers, service providers, novel funding methods and user innovators.

Personal 3D Printing Market: Data

Industry observers estimate that 72,503 personal 3D printers were sold in 2013, with total revenues accumulating to $87.6 million. This accounted for 9 % of the revenues generated in the overall 3D printing market. The average selling price of a personal 3D printer was $1,208 in 2013 (Wohlers Associates 2014, pp. 124-125).

Many of the personal 3D printers have their origins in the RepRap project (http://www.reprap.org). RepRap was started by Adrian Bowyer at the University of Bath as an open source project in 2005. The goal was to create a 3D printer which could replicate itself. All of the designs of the project have been released under the GNU General Public License (GPL). The project relies on about 25 core contributors and a large support community, which consists of enthusiasts, early adopters of emerging technologies, hackers and academic researchers (Jones, Haufe et al. 2011). For intellectual property scholars, RepRap is an interesting example illustrating that the open source idea may not only work for computer software, but also for the creation of physical products.

Personal 3D printers include RepRap and its derivatives, as well as printers sold by MakerBot, Delta Micro Factory, 3D Systems and many other companies. While some manufacturers operate both in the industrial and the personal 3D printing sector (e.g. 3D Systems), others focus only on the consumer market. Another open-source 3D printer project, Fab@Home (http://www.fabathome.org), has developed a multi-material 3D printer which can print anything from chemical reactants to silicone sealant and chocolate.

Many members of the personal 3D printing movement are members of the RepRap community and embrace values of the open source community. This has also facilitated the creation of specialized 3D printing software programs, which are either licensed under open source licenses or under proprietary copyright licenses, but are provided for free. Open source slicer programs, such as Slic3R and Cura, convert STL descriptions of an object into so-called "G-code" file instructions tailored to specific 3D printers. They are often included in 3D printing clients such as Repetier-Host. Autodesk also offers various free 3D printing design software programs.

The emergence of the open source 3D printing community raises the question for intellectual property scholars why developers decide to invest considerable time, money and effort in creating open source 3D printers, without the ability to recoup their investment through the intellectual property system. The motivations of open source 3D printer developers may be similar to developers of other open source products (Lerner and Tirole 2002). In particular, personal needs, intrinsic motivation and reputational goals may be important driving factors for developers of open source 3D printer hard- and software (Jong and Bruijn 2013, p. 45). In addition to open source hardware and software, the personal 3D printing market is characterized by specialized service providers which allow users to share 3D design files and/or use centralized 3D printing services to print 3D objects and have them shipped to the user. Companies such as Ponoko, Sculpteo and Shapeways operate marketplaces where producers of 3D objects can sell their models to consumers. The consumer can then either print the physical object at home or have it printed by the marketplace. The marketplace Shapeways, for example, was founded in 2008 as a spin-off from Royal Philips Electronics. The company operates a large 3D printing facility in Long Island City, NY. It shipped one million 3D-printed parts in 2012 (McKinsey Global Institute 2013, p. 109). In 2014, the company featured nearly 500,000 3D objects, and 23,000 shop owners and products designers from 133 different countries.[3]

Other platforms focus on the sharing of 3D design files. The platform Thingiverse, which is operated by MakerBot, for example, allows the uploading and sharing of user-created digital design files. It now features over 400,000 design files and is widely used by the RepRap and related communities. Empirical research is starting to explore user behavior on such platforms (Moilanen, Daly et al. 2015; Mendis and Secchi 2015, pp. 24 et seq.). Furthermore, established companies from related industries are exploring entering the market for personal 3D printing services Companies such as Office Depot, Staples and UPS are currently offering 3D printing services on a trial basis in a select number of their stores.

[3] Mansee, Shapeways in 2014: A Year in 3D Printing and What's Next for 2015, Dec. 29, 2014, http://www.shapeways.com/blog/archives/19390-shapeways-in-2014-a-year-in-3d-printing-and-whats-next-for-2015.html.

In addition to novel service providers, the personal 3D printing community also benefits from novel funding mechanisms. Various personal 3D printing projects have benefited from crowdfunding platforms, such as Kickstarter. M3D raised $3.4 million, Formlabs $2.9 million and WobbleWorks $2.3 million on Kickstarter for 3D printing-related projects (Wikipedia 2015). Some of the crowdfunded projects may have proven popular on Kickstarter because of the media hype surrounding personal 3D printing technologies. But they also demonstrate the ability of this community to raise funds in novel ways.

Most importantly, the personal 3D printing market is characterized by many “user innovators” who are not mere consumers of a product, but who like to tinker with it. They may, thereby, explore new usage scenarios for 3D printers. As many of the personal 3D printers are based on open source software and hardware, sophisticated users are able to alter and improve upon existing hardware and software designs. In the personal 3D printing market, a particular interaction between companies and user innovators blurs the boundaries between producers/innovators and consumers (“maker movement”) (Lipson and Kurman 2013, p. 48; Bechthold, Fischer et al. 2015, pp. 37, 70; Pearce 2012). The personal 3D printing market is, therefore, an example of a market in which user innovation plays an important role (Hippel 2005). It could lead to a world in which products are designed and produced based on commons-based peer-production models (Benkler 2002; Kostakis and Papachristou 2014).

3D Printing and Intellectual Property Rights

As the preceding sections have demonstrated, the 3D printing industry is diverging in two directions. On the one hand, the industry serves the manufacturing sector with specialized high-quality and expensive 3D printing systems and services. On the other hand, an end-consumer market has developed over the last few years, with low-cost personal 3D printers being sold under $1,000 and service providers offering 3D printing services to end consumers. These two markets are rather distinct, not only as far as customers, costs and future development are concerned. They also raise different issues for the intellectual property system.

6. Industrial 3D Printing
a) Patent Protection

Patent protection seems to have played a considerable role in the industrial 3D printing sector. The following subsection will focus primarily on patents for 3D printers, components and processes used in such printers. Early inventors in the industry made active use of the patent system to receive legal protection on their inventions (see supra Section II 2). More systematic analyses of patents related to 3D printing reinforce this impression.

Various attempts have been made to analyze 3D printing patents. A study by Gridlogics Technologies identified 2,653 relevant patents (Gridlogics 2014, p. 5). A study by the U.K. Intellectual Property Office identified 9,145 relevant patents, equating to 4,015 patent families (U.K. Intellectual Property Office 2013, p. 10). The difference in the number of relevant patents is most likely a result of different search and identification strategies, which are complicated by the fact that, for a long time, no specific subclass for 3D printing technologies existed in international patent classifications.

Both studies identify top patent holders in the 3D printing sector. According to the study by the U.K. Intellectual Property Office, top patent holders include Fujitsu, Stratasys and 3D Systems. The most important university patent holder is the University of Texas System (U.K. Intellectual Property Office 2013, p. 19). According to the study by Gridlogics Technologies, top patent holders include 3D Systems, Stratasys, MIT and HP (Gridlogics 2014, p. 9).

A study by Yen-Tzu and Hsin-Ning identifies 3D Systems and MIT as the top patent holders in 3D printing technologies. They state that the ten top patent holders own about 26 % of all 3D printing patents (Yen-Tzu and Hsin-Ning 2014, p. 1411).

Many of the top patent holders are companies based in the U.S., although the inventors are not necessarily based in the same country (U.K. Intellectual Property Office 2013, pp. 3, 17). According to various studies, the top priority countries are the U.S., Japan and China (U.K. Intellectual Property Office 2013, pp. 13-14; Gridlogics 2014, p. 11; Expertenkommission Forschung und Innovation 2015, pp. 76-77). This may be used as a rough indication of the origin of the inventions which are patented. The study by the U.K. Intellectual Property Office also provides an overview of the top IPC classifications in which 3D printing patents exist (U.K. Intellectual Property Office 2013, pp. 23-24).

The study by the U.K. Intellectual Property Office has also identified 3D printing-related patents with the most forward citations, which can be used as a measure of patent quality. These patents are (U.K. Intellectual Property Office 2013, p. 25):[4]

U.S. Patent number	Applicant	Publication date
5,204,055	MIT	Apr. 20, 1993
4,863,538	University of Texas System	Sept. 5, 1989
5,518,680	MIT	Feb. 7, 1995
5,387,380	MIT	Feb. 2, 1995
6,259,962	Object Geometries Ltd.	Jul. 10, 2001

Table 1: 3D printing patents with most forward citations, according to U.K. Intellectual Property Office (2013)

Anecdotal evidence suggests that 3D printing companies are enforcing patents, at least in some cases. Some companies, including 3D Systems, DuPont, EOS, Envisiontec and Stratasys, have been involved in patent litigation covering patents related to 3D printing. Yen-Tzu and Hsin-Ning (2014), p. 1412, identified only seven 3D printing-related patents which have been litigated up to 2012 (U.S. patents no. 5,059,359; 5,137,662; 5,184,307; 5,345,391; 5,370,692; 6,942,830; 7,735,542), although the authors do not provide detailed information on their identification strategy.[5]

The patents described above cover 3D printers, components of such printers and 3D printing manufacturing processes. Patent protection is not only an important strategy for these parts of the 3D printing ecosystem. Patents may also cover 3D printing raw materials, such as powders, filaments, liquids or sheets. Up to now, there has been very limited reports on patents playing an important role in the development of raw materials for 3D printing purposes. This may be because many of the materials that are used by 3D printers are not developed especially for 3D printers. Rather, they are general-purpose materials that could be covered by broader patents. Identifying such patents through patent searches is difficult, as their description may not include any reference to 3D printing technologies. This may also explain why there seems to be virtually no scholarly literature exploring the impact of 3D printing raw material patents on the development of the 3D printing industry.

Another reason why there is less reporting on patents on 3D printing raw materials is that these materials have often been used by other industries for many years. This lack of novelty could limit the importance of patents. However, patents on 3D printing raw materials may become more important as raw printing materials become more diverse and as advanced printing materials are modified for use in 3D printers. In addition, 3D printer manufacturers may have a strategic interest in protecting raw printing material with intellectual property

4 Another such list, which only partially overlaps with the list by the U.K. office, is provided by Yen-Tzu and Hsin-Ning (2014), p. 1411.

5 This list is likely to be incomplete. For another litigated patent, see infra Section IV 2 a cc.

rights in order to monopolize the secondary market for printing supplies (see infra Section IV 1 a dd).

b) Other IP Rights

The industrial 3D printing sector does not only rely on patent law in its protection strategy. Trade secret protection plays a considerable role as well. Such protection is less stable than patent protection, because it is costly to keep know-how secret, and the legal protection does not help against independent reverse engineering. Still, it is an attractive tool of protection for the 3D printing industry as 3D printers and 3D objects do not often reveal the details of the manufacturing process that led to the machine or product, which makes reverse engineering difficult (Wohlers Associates 2014, p. 194).

CAD and slicer software programs are often protected by copyright law. As a result, a full industrial 3D printing system will typically touch upon various intellectual property rights: patent rights of 3D printing components, processes and raw printing material, trade secret protection of 3D printing manufacturing processes, copyright protection of controlling software programs, design protection of 3D object designs, and trademark protection for the 3D printer itself.

As the industry matures, deals between companies that license certain 3D printing components to other companies may become more prevalent. Some current 3D printers are monolithic products developed and produced by one manufacturer. Intellectual property protection could lead to an increasingly compartmentalized 3D printing industry in which companies specialize in particular components in the 3D printing value chain, which are then licensed to other companies which, in turn, assemble these components into full 3D printing systems (on the general relationship between intellectual rights and firm size, see Arora and Merges 2004).

c) Knowledge and Technology Diffusion

No empirical study has analyzed the extent to which researchers and developers in the 3D printing technology area are using existing patent documents as sources of technology disclosure and learning. On the one hand, there is some anecdotal evidence that the expiration of key 3D printing patents has had a positive impact on market entry and follow-on innovation. This could indicate that new market entrants are learning from patented inventions and are building on them once the patents have expired. On the other hand, because of the importance of trade secrets in the industry (see supra Section IV 1 b), there are limitations on the ability of the patent system to fully disclose inventions on 3D printing processes.

Publications in scientific journals may also play a role in knowledge diffusion. The number of 3D printing-related scientific publications has more than tripled between 2000 and 2013, from 477 to 1793 publications per year (Expertenkommission Forschung und Innovation 2015, pp. 71, 75). Researchers from the United States and China have been most productive, as measured by their citation-weighted publications, followed by researchers from Germany and the United Kingdom (Expertenkommission Forschung und Innovation 2015, pp. 75-76). However, in general, it is difficult to identify the actual channels of knowledge diffusion in the industrial 3D printing industry, and no empirical study has focused specifically on this issue.

It is also difficult to assess the degree of technology diffusion across different continents. Only limited data on installed 3D printers in various continents exists. Lipson and Kurman (2013), p. 34, report that about 40% of the world's 3D printers are located in the United States, while about 10% are located in Germany and Japan each, and about 8.5% are located in China. A rough indication could be the number of industrial 3D printers sold by 3D printer manufacturers located in various countries. According to Wohlers Associates (2014),

p. 122, U.S.-based manufacturers sold 42308 industrial 3D printers between 1988 and 2013. Israeli manufacturers sold 11601, German manufacturers 6766, Chinese manufacturers 2382, and Japanese manufacturers 1887 printers. Of course, such data only tell us which company has produced the printers. They do not tell us where the printers are installed.

7. Personal 3D Printing

While the relationship between the 3D printing industry and the intellectual property system does not seem special as far as the industrial 3D printing sector is concerned, the personal 3D printing sector shows a different picture. It is challenging for intellectual property owners whether and how they can enforce their rights in this sector (see below Section IV 2 a). It also raises fundamental questions about various mechanisms to incentivize innovation in the 3D printing sector (see below Section IV 2 b).

a) Protection Strategies

aa) Protection of 3D Printers and Printing Processes

Owners of patents on 3D printers or 3D printing processes are facing new challenges in a world in which end users are sharing 3D design files on specialized marketplaces and printing 3D objects on their own 3D printers. From a legal perspective, whether a consumer engages in patent infringement by printing 3D objects on his own printer or sending it to a 3D printing service depends on the extent to which patent protection also covers actions of consumers for private purposes. In the patent laws of some countries, such as the United States, no exception for private or non-commercial use exists (on the implications for 3D printing, see Desai and Magliocca 2014, pp. 1716-1717). In other countries, including many European countries, patent laws have specific provisions excluding private and non-commercial uses from the exclusive rights of patent owners (WIPO Standing Committee on the Law of Patents 2013).

From a practical perspective, suing countless consumers for potential patent infringement who are using their own 3D printers to reproduce 3D objects is a highly unattractive option for patent owners. Identifying all these consumers is complicated and costly; the financial resources of consumers to pay damages are limited; some of them are likely to reside in jurisdictions in which patent enforcement is not an easy task; and it may not be a wise business strategy for manufacturers of personal 3D printers and services to bring their own customers to court. The rise of personal 3D printers, which can be built by end users and which can partially replicate themselves, could, therefore, lead to a world of massive patent infringement by consumers.

Even if an action by a consumer constitutes potential patent infringement, not every use of an invention is sufficient for an infringement action. If a consumer wants to repair his own product, such repair – which does not constitute patent infringement – has to be distinguished from a reconstruction of the patented invention – which does constitute infringement. 3D printing creates new challenges for this distinction between repair and reconstruction, which exists in many patent systems (for a discussion of U.S. patent law, see Wilbanks 2013; for a discussion of U.K. patent law, see Mendis 2013, pp. 160-161; for a discussion of German patent law, see Bechtold 2007).

bb) Protection of 3D Designs

Consumers may not only own and operate their own 3D printers, they may also feed them with 3D design files which they may have downloaded from an online marketplace. In addition, they may alter existing 3D design files with specialized software and create three-dimensional reproductions of such modified 3D designs. It is questionable whether the original creators of the designs can enforce some intellectual property rights against consumers in case of unauthorized reproduction or alteration of original designs.

From a legal perspective, the shape of an object and its digital representation in a 3D design file may be protectable through various kinds of intellectual property law. If the shape of an object has a sufficient level of originality and is not solely a functional design, it may be copyrightable (Mendis 2013, pp. 165-167; Dasari 2013, pp. 288-305; Li et al. 2014, pp. 325-328; Mendis and Secchi, 2015, pp. 7-15). It may also be subject to design protection (Mendis 2013, pp. 163-165). The object's digital representation in a 3D design file may be copyrightable as an artistic work or computer program, although this may raise issues with regards to originality standards and merger doctrines of the copyright laws of individual countries (Desai and Magliocca 2014, pp. 1705-1709; Dasari 2013, pp. 288-305; Mendis 2014, pp. 269-271; Li et al. 2014, pp. 325-328; Mendis and Secchi 2015, pp. 7-15). The three-dimensional reproduction of such a file may then itself be an infringement of the reproduction rights granted by copyright and design protection (Mendis 2014, p. 273; Li et al. 2014, pp. 327-328; Dasari 2013, pp. 305-315). If a user alters an existing 3D design file and creates a three-dimensional representation of such design, this may infringe reproduction and modification rights as well. Ultimately, whether and to what extent 3D designs and 3D design files are copyrightable, and whether their reproduction violates copyright protection will depend on the details of the originality standards in the copyright statutes and case law of individual countries (for a discussion under EU and U.K. copyright law, see Mendis 2014; Li et al. 2014; Mendis and Secci 2015, pp. 7-15; for a discussion under U.S. copyright law, see Dasari 2013).

In general, from a practical perspective, rights owners of 3D design files face similar problems to owners of patents on 3D printer production of processes: it is hard to identify consumer infringers, costly to enforce intellectual property rights against them, and it may not be the optimal business strategy to sue your own customers.

cc) Indirect Liability

Intellectual property rights are difficult to enforce against end consumers in the emerging world of personal 3D printing. When it becomes difficult to enforce rights against parties who are direct infringers, rights owners often target other parties who are indirectly facilitating or even encouraging these infringements. A prime example of such intellectual property enforcement strategy is the discussion of intermediary liability for Internet service and online content providers for copyright infringement (Landes and Lichtman 2003).

3D printing is facing a similar discussion. Should operators of 3D design marketplaces be liable for infringing 3D designs that are shared over their marketplace? Should providers of 3D printing services be held liable for the 3D prints they are performing on behalf of their customers? In fact, 3D design file marketplaces such as Thingiverse have already been subject to notice and takedown orders under the U.S. Digital Millennium Copyright Act (Mendis 2013, p. 159).

As the transactions costs of suing direct infringers are becoming prohibitively expensive, holding intermediaries liable seems attractive at first sight. However, one has to be careful not to push intermediary liability too far, as intermediaries perform many beneficial functions in the 3D printing market. They enable new marketplaces for sharing and distributing content, and facilitate distributed manufacturing. Increasing intermediary liability, therefore, runs the risk of stifling innovation in distribution and manufacturing technologies.

This tradeoff between incentivizing inventors and creators through intellectual property rights and incentivizing manufacturers of distribution technologies and services is well-known from copyright problems created by Internet piracy (Wu 2005; Lemley and Reese 2004). In order to find a proper balance between these interests, courts and legislators in many jurisdictions have tried to adapt rules and standards of contributory and vicarious liability, and to create specific exemptions from liability for intermediaries. This includes tailored notice-and-takedown procedures and inducement standards (Desai and Magliocca 2014, pp. 1713-1719; Doherty 2012; Brean 2013; Li et al. 2014, pp. 330-331; Ballardini et al. 2015, pp. 857-865).

This discussion is not only relevant for 3D printing marketplaces and service providers. It can also affect institutions providing funding to 3D printing developers. In 2012, 3D Systems filed a patent infringement lawsuit against FormLabs for infringing its stereolithography U.S. Patent no. 5,597,520 (issued on Jan. 28, 1997). 3 D Systems also named Kickstarter as a defendant in this lawsuit, alleging that Kickstarter had promoted FormLabs and assisted it in raising $2.9 million from a crowdfunding campaign to create a printer competing with 3D Systems. This resembles litigation strategies of the music industry, which, when suing the first peer-to-peer file-sharing network Napster, also named investors such as Bertelsmann and venture capitalists as defendants (Lemley and Reese 2004).

dd) Implications

These developments point towards a future of mass-scale infringement of 3D printing-related intellectual property rights by end consumers with limited abilities of rights owners to enforce their rights effectively. It could be that in the future, the personal 3D printing industry will come to the same crossroads that other digital industries – from software and web development to the music and movie industries – have reached in the past (Desai 2014; Desai and Magliocca 2014; Depoorter 2014).

Operating in such an environment is a challenging task, and will most likely require substantial trial and error by industry participants. In general, companies can adopt various strategies. First, they can use their resources to fiercely enforce their intellectual property rights. Unfortunately, experience from the content industries raises doubts whether this is a viable long-term business strategy (Depoorter 2014; Lemley 2015, pp. 499-502).

Second, industry players can try to use technological protection measures to protect their business models. In fact, in 2012, Intellectual Ventures received a patent on the application of Digital Rights Management technologies to 3D printing technologies. The patent describes a system in which a 3D printer assess whether a 3D design file has an authorization code that grants access for printing. The system implements copy-control technologies for 3D design files (U.S. Patent no. 8,286,236, issued Oct. 9, 2012; on DRM in general, see Bechtold 2004). Other companies are exploring various labeling techniques to identify unauthorized reproductions (Ghilassene 2014, pp. 15-17). Furthermore, some 3D design files marketplaces – for example, Authentise, FabSecure, Secure3D and ToyFabb – offer the possibility to securely stream files directly to the consumer's 3D printer. In such environment, the consumer does not receive the 3D design file, thereby reducing the risk of unauthorized 3D design file sharing (Mendis 2014, p. 280; Desai and Magliocca 2014).

As a third option, 3D printer manufacturers may devise business strategies in which they shift their profits from 3D printers to supply material, in particular to raw printing materials, such as powders, filaments, liquids or sheets ("razor and blades business model"). If a 3D printer manufacturer succeeds in being the dominant supplier of raw printing materials for its printers, it can effectively subsidize the potentially low profit margins on the printer market with higher profit margins on the raw materials market. Many manufacturers of personal 3D printers have already adopted this business model. They provide their own proprietary material. Cartridges with 3D printing raw material cost about 30 € per cartridge (Bechthold, Fischer et al. 2015, p. 39). Such business strategy cannot only be observed with personal, but also with industrial 3D printers (Lipson and Kurman 2013, p. 82). According to news reports, 3D printer manufacturer 3D Systems achieved a margin of 73% on materials, while only achieving 36% on its printers (Powley 2015). Examples from other technology industries show that intellectual property rights can play an important role in controlling such secondary markets for product supplies. Controlling secondary markets through intellectual property rights raise intricate policy problems at the intersection of antitrust and intellectual property law. On the one side, protecting secondary markets with intellectual property rights may provide necessary incentives to inventors on primary or secondary markets. On the other hand, such protection may enable inventors to monopolize secondary markets (Hovenkamp, Janis et al. 2009, § 13.3d; Bechtold 2007, pp. 79 et seq.).

Fourth, companies may try to benefit from the disintegration of value chains caused by 3D printing technologies. Consumer-oriented companies could specialize in designing their products and marketing them under their own brand, while outsourcing the actual production of the product to specialized 3D printing farms or to service providers located close to the consumer. In such a world inspired by Apple's business model, the most important intellectual property right for the 3D printing design company may not be patent protection, but trademark protection for its brand (Desai and Magliocca 2014, p. 1712).

Fifth, companies may decide to embrace their user innovators by adopting improvements of their products that have been developed by end users. This cannot only be a free resource for product improvement, it can also enable new relationships between product manufacturers and end users (Jong and Bruijn 2013, p. 50).

Sixth, companies may decide to acquire startups founded by 3D printing community members, thereby integrating their invention and know-how before they develop into real competitors. 3D Systems, for example, used its acquisition of Bits from Bytes – a producer of low-cost personal 3D printers – as a foothold into the hobbyist sector (Jong and Bruijn 2013, p. 50).

Finally, companies may try to actively facilitate innovative user communities focusing on their products, thereby shaping these communities and creating feedback loops between the company and the communities (Jong and Bruijn 2013, p. 50). This may also include novel branding strategies in which trademarks are used to create fan communities with strong loyalty to a 3D printer producer or service provider.

More generally, experience with other digital technologies suggests that industries are often forced to cope with piracy problems by changing their business strategies and embracing infringing user behavior, rather than fighting against it (see also Lemley 2015, pp. 502-503). It is too early to tell whether the 3D printing industry will successfully calibrate its business strategies for the personal 3D printing market. However, the great variety of novel business models that are tried out in this market demonstrates that the industry is aware of this challenge.

b) The Rise of Open Source 3D Printing

The 3D printing industry has to cope with intellectual property infringements in the personal 3D printing sector. This raises the question why the industry has not been able to keep the development of the personal 3D printing sector under better control, by enforcing their intellectual property rights at a time when the personal 3D printing sector was still in a nascent stage. In other words, it is not obvious how an open source 3D printing ecosystem could evolve, given that many of the technologies used in this ecosystem had originally been covered by 3D printing patents.

Anecdotal evidence suggests that the rise of the open source 3D printing ecosystem was strongly linked to the expiration of key patents (Wohlers Associates 2014, p. 14). RepRap and most other open source 3D printing platforms are based on the fused deposition modeling technique which Scott Crump developed in the late 1980s and which were commercialized by Stratasys (see supra Section II 2). Open source implementations of fused deposition modeling only appeared after related key patents had expired. Prices for 3D printers based on fused deposition modeling have dropped tremendously thereafter.

As the following overview indicates, some key patents on 3D printing technologies have already expired some time ago. However, a number of important patents expired between 2013 and 2015 (see also Hornick and Roland 2013; Bechthold, Fischer et al. 2015, p. 7):

Technology	U.S. Patent Number	Filing Date	Priority Date	Publication Date	Expiration Date
Fused deposition modeling	5,121,329	Oct. 30, 1989	Oct. 30, 1989	June 9, 1992	Oct. 30, 2009
	5,340,433	June 8, 1992	Oct. 30, 1989	Aug. 23, 1994	Aug. 23, 2011
	5,503,785	June 2, 1994	June 2, 1994	Apr. 2, 1996	Jun. 2, 2014
	5,529,471	Feb. 3, 1995	Feb. 3, 1995	June 25, 1996	Feb. 3, 2015
	5,555,176	Oct. 19, 1994	Oct. 19, 1994	Sept. 10, 1996	Oct. 19, 2014
	5,572,431	Oct. 19, 1994	Oct. 19, 1994	Nov. 5, 1996	Oct. 19, 2014
Selective laser sintering	4,863,538	Oct. 17, 1986	Oct. 17, 1986	Sept. 5, 1989	Oct. 17, 2006
	5,597,589	May 31, 1994	Oct. 17, 1986	Jan. 28, 1997	Jan. 28, 2014
	5,639,070	June 7, 1995	Oct. 17, 1986	June 17, 1997	Jun. 17, 2014
	5,733,497	Sept. 13, 1995	Mar. 31, 1995	Mar. 31, 1998	Mar. 31, 2015
Stereo-lithography	4,575,330	Aug. 8, 1984	Aug. 8, 1984	Mar. 11, 1986	Aug. 8, 2004
	4,929,402	Apr. 19, 1989	Aug. 8, 1984	May 29, 1990	May 29, 2007
	4,999,143	Apr. 18, 1988	Apr. 18, 1988	Mar. 12, 1991	Apr. 18, 2008
	5,174,931	Apr. 27, 1990	Sept. 26, 1988	Dec. 29, 1992	Dec. 29, 2009
	5,494,618	June 27, 1994	June 27, 1994	Feb. 27, 1996	Jun. 27, 2014
	5,569,349	June 5, 1995	Oct. 4, 1990	Oct. 29, 1996	Oct. 29, 2013
	5,597,520	Apr. 25, 1994	Oct. 30, 1990	Jan. 28, 1997	Jan. 28, 2014
	5,609,812	Sept. 14, 1993	Apr. 18, 1988	Mar. 11, 1997	Mar. 11, 2014
	5,609,813	June 7, 1995	Apr. 18, 1988	Mar. 11, 1997	Mar. 11, 2014
	5,610,824	Jan. 25, 1993	Oct. 17, 1989	Mar. 11, 1997	Mar. 11, 2014
	5,630,981	June 6, 1995	Aug. 8, 1984	May 20, 1997	May 20, 2014
	5,651,934	Mar 13, 1995	Sept. 26, 1988	Jul. 29, 1997	Jul. 29, 2014
	5,762,856	June 7, 1995	Aug. 8, 1984	Jun. 9, 1998	Jun. 9, 2015
3D design files	5,587,913	Oct. 12, 1994	Jan. 15, 1993	Dec. 24, 1996	Dec. 24, 2013

Table 2: 3D patents which expired in or before 2015

While improvements patents may still cover important aspects of the current technology space, commentators have speculated whether the large number of patents related to stereolithography which expired recently could lead to a development of open source stereolithography 3D printing, similar to the impact expired patents on fused deposition modeling had on the RepRap community.

This indicates that patents on 3D printing technologies may influence the development of open source 3D printing solutions. Once the relevant patents had expired, the threat of injunctive relief against open source 3D printers vanished. While it is difficult to show that the expiration of key patents actually caused the emergence of the open source 3D printing community, some anecdotal evidence suggests such causal relationship (Lipson and Kurman 2013, pp. 231-234; West and Kuk 2014, p. 8; Bechthold, Fischer et al. 2015, pp. 8, 39, 42; Campbell, Bourell et al. 2012, p. 257).

However, other factors may have been equally important in facilitating the emergence of the open source 3D printing community. The availability of 3D design software which is easy to use, the emergence of communication platforms such as Wikis, weblogs, mailing lists, and online chat systems, of open source version control systems and software repositories as well as of online market places have all contributed to a digital communication infrastructure which is crucial to the collaborative innovation ecosystem upon which the open source 3D printing community is built (Bechthold, Fischer et al. 2015, p. 37; West and Kuk 2014, p. 7). Developers in the open source 3D printing community also learned from the open source software community and adopted similar design and policy approaches. Furthermore, as computer and Internet broadband penetration increased around the globe, creating worldwide developer communities became easier. Finally, hardware components that are used in the development and production of open source 3D printers have become cheaper and easier to use over the years (West and Kuk 2014, pp. 6, 25).

All this indicates that it is difficult to quantify the impact patent expiration had on the emergence of the open source 3D printing community. It arguably had some positive impact, although many other factors were also crucial in the emergence of this community.

c) Knowledge and Technology Diffusion

Knowledge and technology diffusion in the personal 3D printing sector seem to take place through different channels. For commercial manufacturers of personal 3D printers, knowledge and technology diffusion does not seem to differ much from the industrial 3D printing sector (see supra Section IV 1 c). For the open source 3D printing community, knowledge and technology diffusion has taken different paths.

As indicated above, there is some anecdotal evidence according to which open source developers waited for key 3D printing patents to expire. This may provide some indirect evidence that patents, in this industry, disclose useful information to follow-on innovators who want to build upon existing inventions. The development of open source 3D printers would, arguably, not have been possible without the advances the industrial 3D printer manufacturers had achieved over the preceding 20 years. The emergence of the open source 3D printing community may, therefore, be a good example of learning and technology adoption from one (large-scale, industrial) market to another (individualized consumer) market. However, equally important tools for knowledge diffusion in the open source 3D printing community are based on modern communication technologies (see supra Section IV 2 b).

No aggregated information is publicly available on the number of personal 3D printers installed in different continents or countries. However, the emergence of open source 3D printing technologies could have an impact on technology adoption in developing countries. Various projects explore the extent to which personal 3D printers could enhance access to both basic products (clothes, kitchenware or toilets) and advanced consumer goods in developing countries (Bechthold, Fischer et al. 2015, pp. 70-72; Pearce 2010).

Conclusion

3D printing technologies have their roots in manufacturing inventions in the 1980s. While it was initially used to accelerate prototyping processes, 3D printing is increasingly being used to print product components or even finished products. While the technological development is still in flux, some stable patterns have emerged. Over the years, the technology has evolved into two distinct directions. In the industrial 3D printing sector, patent protection seems to have played an important role, which is not that different from other manufacturing industries. In the newly emerging personal 3D printing sector, the intellectual property system faces new challenges. Developers of personal 3D printing systems and services have to cope with large-scale infringement by end consumers. This situation well-known from digital content technologies. At the same time, the expiration of key patents on 3D printing has arguably contributed to a flourishing ecosystem of open source 3D printer hardware and software. Once the open source 3D printing community has begun to flourish, it does not rely on intellectual property protection as an appropriation mechanism. Also, knowledge and technology diffusion takes place through various channels in the 3D printing industry. Diffusion through the intellectual property system may play a certain role. Diffusion via scientific publications and modern communication technologies are also significant.

As in many areas of innovation policy, it is difficult to establish a causal link between the level of intellectual property protection and innovation in the 3D printing sector. Anecdotal evidence suggests that the impact the intellectual property system has had on the evolvement of the 3D printing sector is complex. On the one hand, patent protection seems to be an important component of business strategies in the industrial 3D printing sector. On the other hand, a vibrant open source community in the personal 3D printing sector has emerged. Intellectual property protection played a beneficial role on 3D printing technologies in some instances (sometimes intended and sometimes unintended), and it may have played a neutral or detrimental role in other instances. Studying the progress of 3D printing technologies thereby also informs us about the intricate relationship between intellectual property and innovation in general.

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