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Do Patents Spur Innovation for Society? Lessons from 3D Printing

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Abstract

Effective appropriation of new technology has long been considered essential for innovation. Yet, the role of patents and other Intellectual Property tools has been questioned, both for rewarding innovators and serving societal needs. Simultaneously, there is ample empirical evidence of technological advance accelerating under conditions of loose appropriability, for example, when patents expire and cases of innovations based on shared technology and diverse motivations. This paper explores the case of the 3D printing technology, which appears to have found successful commercialization and dynamic market growth after key patents expired. We analyze the role of commons-based peer production practices in forging synergies among different factors and effectuating an alternative innovation pathway and the challenges and contradictions in the process. Finally, we critically assess recent developments of 3D printing technology and draw lessons for innovation policy by incorporating aspects of emerging commons-based innovation paradigms.

Keywords

property rights; innovation policy; 3D printing; peer production; digital commons; open innovation

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1. Introduction

Patents, and Intellectual Property, more broadly, are a heavily contested topic in Science, Technology, and Innovation (STI) policy. Yet, despite the critique and empirical cases against patents, they are still considered an indispensable ingredient for successful innovation. The conventional understanding of innovation as successful market exploitation of new knowledge and technology justifies the importance of patents. They are essential institutions that allow the appropriation of knowledge and technology.

Innovation requires broad and heterogenous knowledge diffusion and experimentation processes, including formal and informal actors engaging in diverse relations. A wider variety of ideas, agents, motivations, and potential combinations within innovative processes can increase the scope for new and more sophisticated innovations (Fagerberg, 2006). Moreover, free flows of knowledge and collaboration across different sectors are essential for a solid scientific base to yield the types of practical research payoffs that innovation builds upon, which are more serendipitous than calculated in advance (Nelson, 2004).

There is growing evidence that strong patents do not necessarily favor technological advance and innovation, nor do they singlehandedly secure successful market exploitation. Moreover, when patents do deliver innovation, they arguably foster a particular configuration of the socio-technological options available that best conforms to the institutional environment the patent system creates, to begin with.

The broad diffusion of Information and Communication Technologies following the digital revolution has effectuated unseen capabilities for knowledge and technology sharing across diverse groups of experts and laypeople. The phenomenon Benkler (2001; 2006) documented as commons-based peer production (CBPP) displayed a series of innovations that were based on a different set of institutional arrangements. With no pre-defined roles or structure, dispersed individuals and groups can freely collaborate with no exclusive control over productive resources such as knowledge, information, software code, and design and openly share the results. From free and open-source software (FOSS) projects to the free encyclopedia Wikipedia and open hardware, CBPP demonstrates an alternative configuration of knowledge and technology that can produce socially meaningful outcomes.

From this perspective, in this article, we review the case of 3D printing technology, focusing on the Fused Deposition Modelling (FDM) patent. We aim to critically explore the role of patents in the shaping of the 3D printing socio-technological system, alongside diverse factors that contributed to its development outside of- and essentially threatened- by the patent regime. FDM is an interesting case for two main reasons. First, it has been one of the key methods in the development and broad diffusion of 3D printing and is still considered the most popular method (Sculpteo, 2021). Second, in the years following the expiration of the FDM patent in 2009, the technology co-evolved alongside shared socio-technical imaginaries of distributed design and a new industrial paradigm (Bechtold, 2016).

In the following sections, we attempt to interpret alternative technological trajectories in the development of disruptive technologies that may lead to different, possibly more socially relevant, socio-technological outcomes. Section 2 summarizes the main strains of critique on patents as a paradigmatic form of Intellectual Property Rights (IPRs), followed by a brief analysis of the CBPP innovation dynamics. Section 3 explores the FDM case before discussing the main lessons and implications for STI policy in section 4 and summarizing our conclusions in section 5.

2. Theoretical framework: patents as engines of innovation, critique, and alternative paradigms

This section presents the primary literature critically engaging with the conventional understanding of the function, outcomes, and limitations of patents and IPR in innovation. It guides our analysis of the historical factors affecting knowledge and technology production in our case study afterward, highlighting various challenges and trade-offs.

2.1. Patents and innovation

The appropriation of new knowledge and technology is considered of utmost importance in the ability of innovators to seize the benefits from innovation. Capitalism is often seen as a system fueled by dynamic imperfect competition and rent-seeking behavior (Reinert, 2007). Knowledge, a non-rival good, is associated with a general inability of markets to motivate rent-seeking behavior under perfect competition (Arrow, 1962). Patents create artificial scarcity and are thus a structured form of rent-seeking that allows profitability, which would otherwise not be possible under perfect competition (Reinert, 2007). From this perspective, the degree of appropriability of knowledge is paramount in enabling entrepreneurs to profit from innovation.

In his seminal piece for STI policy, Teece (1986) identifies three building blocks for profiting from innovation: (a) appropriability regimes; (b) complementary assets; and (c) a dominant design paradigm. Appropriation is thus only one of the necessary conditions that allow market exploitation of knowledge and technology, while IPRs are one form of appropriation among several options. Furthermore, appropriation mechanisms are contingent on the nature of knowledge, leading to different organizational and innovation patterns among various firms and sectors (Pavitt, 1984; Teece, 1986; Kristensen, 1999). Different modes of organization and production can lead to higher or lower capacity for innovation related to specific technological regimes.

However, in contemporary discourse, the tools through which firms can reap the benefits of innovation have been somehow reduced to appropriability regimes. The latter, then, further reduced to refer almost exclusively to IPRs, and, finally, patents in particular (Dosi et al., 2006). With the very role of IPRs for both innovators and the economy increasingly being questioned, the "stronger patents are always better" creed (Nelson, 2006, p. 1109) seems to be more of an ideological fixation of actors dominating patent law and practice than an empirical fact.

Conventional debates on the theory and practice of IPRs largely revolve around market failures, i.e., the inability of innovators to benefit from their innovations through market functions. This proposition ignores qualitative characteristics of knowledge and technology and presumes a linear relation between patents and innovation (Dosi et al., 2006). Hence critique on patents concerns both the underlying logic of patent laws and their function about the needs they purportedly serve.

Coriat and Weinstein (2009) trace the incumbent paradigm of IPRs regimes back to the 1980s in the USA as a response to the emergence of the knowledge-based economy. They argue the knowledge-based economy is not so much marked by the increasing importance of knowledge for industrial development, which was not all too new at the time. Instead, its distinct trait is a heavy shift towards knowledge commodification. Knowledge now more than ever constitutes a strategic asset (Winter, 1987). The conditions under which economic agents can control and appropriate knowledge and then turn it into a revenue source have become increasingly important (Coriat and Weinstein, 2009).

There is widespread doubt on whether the increase of patents and strong legal protection has been translated into technological advance. In theory, a robust patent system is essential in providing incentives to invent, but in practice, the long-term equilibrium effect can be considered negative (Boldrin and Levine, 2013; Dosi et al., 2006). Based on a significant body of theoretical and empirical data related to the USA patent system, Boldrin and Levine (2013) make a case against patents, arguing that there is no empirical evidence for the claim that patents increase innovation and productivity. Likewise, drawing from the conclusions of scholars who have extensively studied the topic (Jaffe, 2000, Dosi et al., 2006), there appears to be little empirical evidence connecting the unquestionable technological advance that has taken place in the USA over the last three decades with the strengthening of the patent laws.

Therefore, this view that strong patents equal more innovation appears to result from various actors' long-term political and economic pressures on the government-operated patent system. This includes the parties directly concerned rather than the end-users of the technologies and their benefits. As Boldrin and Levine (2013) put it, the patent system is a case where "the regulators act in the interests of the regulated, not the wider public." In this sense, the patent system has rarely been the enabling factor for innovation and the creation of new industries. Instead, it is mature industries that seek legal protection once their growth potential starts diminishing. Historical evidence suggests most innovations occur outside the patent system. At the same time, innovative firms preferred to rely on alternative mechanisms to support their inventions, such as secrecy and lead-time, despite patent laws. For the same reason, the absence of patent laws in some countries does not appear to affect the overall occurrence of innovations (Moser, 2013). The already established industries with an intense lobbying position pressure for stronger patent protection for their mature technologies, rather than the new disruptive ones, seeking to reap the benefits of their innovations (Boldrin and Levine, 2013).

From another perspective, Nelson (2004) argues that the adverse effects from patenting in advanced technologies are not limited to the techno-economic level. There is broad recognition that innovation, as a driving force of capitalism, is empowered by a strong science base, largely a product of publicly funded research (Nelson, 1993; Mowery and Nelson, 1999; Nelson, 2004). The quality of scientific research depends on openness and collaboration, as the practical payoffs of research cannot be predicted but are usually serendipitous and based on the informed judgment of scientists. To this end, non-market incentives, and control mechanisms in academia, such as peer review and mutual scientific acclaim, imperfect as they may be, still appear to function well enough to support quality in science production and the scientific commons (Nelson, 2004).

Similarly, technological advance is “a collective, cultural, evolutionary process” (Nelson, 2004, p. 458). It constitutes a cumulative result of the prior work of many inventors and developers (Nelson, 2004; Scotchmer, 1991). Therefore, the lines between science and technology are pretty blurry, especially in cases of scientific discoveries that simultaneously contribute to scientific research and commercial applications (Murray and Stern, 2005). In the latter case, empirical evidence shows that IPRs restrict the diffusion of scientific results in both science and technology fields. Furthermore, it is debatable whether publicly funded Research and Development (R&D) should be patentable from universities, as is the case in the USA.

Patenting of advanced technologies thus threatens the publicly supported scientific commons, on which these technologies rest (Nelson, 2004; Murray and Stern, 2005). It becomes evident that the cumulative impact of IPRs practices and patents is neither beneficial for science nor the vast majority of inventors and technological innovation in general. A wisely designed patent system that could serve as a driver for innovation and growth is, in principle, possible under the right circumstances. But in the long run, it remains susceptible to political and economic pressures from powerful interest groups (Boldrin and Levine, 2013). The cumulative nature of science and technology poses a significant challenge in designing effective patent laws that would adequately reward early research and innovation for providing the foundations and later innovators for improvements (Scotchmer, 1991). Policies, which grant strong legal protection to early inventors, may pose barriers to further innovation. In contrast, policies that facilitate the diffusion of ideas and the entry of new innovators may prove more effective in encouraging innovation (Moser, 2013).

Finally, discussions around patent laws often ignore qualitative differences to the main determinants of innovation among different economic activities and technologies related to the varying levels of opportunities (Dosi et al., 2006). Such opportunities are found either within the R&D system, the efforts of new or established firms, or into the broader innovation system, stemming from suppliers/users' relationships. It is well known that innovation is essentially a serendipitous phenomenon, and as such, on many occasions, it stems from collective invention (Allen, 1983; Nuvolari, 2004) rather than individual rent-seeking.

Patents often stifle innovation within the broader system or steer it towards other areas than what society might need at a given time, thereby pushing productive forces out of work. An understanding of innovation measured in terms of patents has been shown to have reached its limits (Huebner, 2005), while the yields of such innovation trajectories for society are being questioned (Pansera and Fressoli, 2020). So, if the subject of STI policy is not to merely foster more innovation in the conventional sense, detached from societal needs, but rather to steer productive forces towards a socially meaningful direction, there needs to be another way to understand and foster innovation.

2.2. The emergence of commons-based innovation trajectories

Free and open-source software (FOSS) came into prominence at a time of fierce competition between enterprises ahead of the dot-com bubble as a counterreaction attempting to enable and support the conditions that favor the free circulation of information (Coriat and Weinstein, 2009). There is arguably much more to identify in the practices first observed in FOSS than simply an alternative approach to IPRs. Such practices shift away from the logic of knowledge commodification and instead focus on the rights to access, use and control resources and the production and distribution of shared goods, built upon and along with a knowledge commons (Weber, 2004; Benkler, 2006).

Benkler (2006) coined the term commons-based peer production (CBPP) to document such practices that came to achieve major economic significance in the digital economy (Pazaitis and Kostakis, 2021). There are three critical characteristics identified that distinguish CBPP from traditional capitalist practices: (a) the decentralization of the conception of problems and the execution of solutions; (b) the diversity of participants' motivations and (c) the decoupling of governance from private property and contract (Benkler, 2015; Kostakis et al., 2015).

CBPP projects have demonstrated effective mobilization of creative energy from autonomous individuals and groups, organized in distributed networks, coordinated into open projects, largely without traditional hierarchical organization or, often, any (direct) financial incentives (Benkler, 2006). The produced value is a collective affair among the participants, who are often parts of emerging communities, creating a perceived common good. CBPP practices follow a non-rivalry logic of knowledge and introduce alternative patterns to raise the level of opportunities for innovation through open participation and collaboration.

This way, the peer-to-peer dynamics of CBPP arguably manage to transcend the "market failures" discourse by not requiring formalizations and thus considerably lowering the transaction costs of production (Benkler, 2001; Bauwens et al., 2019). At the same time, they allow users to experiment and adapt to a highly uncertain and changing environment and thus emphasize innovation, resilience, and robustness over efficiency. A few years ago, FOSS or Wikipedia was widely considered exceptions to the rule. Their eventual success represents a core challenge to conventional organizational patterns and knowledge appropriation (Pavitt, 1984; Teece, 1986) based on property and market exchange, with one based on modularity, stigmergic coordination, and motivational diversity (Benkler, 2016; Kostakis, 2019). CBPP thus formulates an alternative trajectory for the deployment of the digital revolution that can be innovative, as well as democratic and sustainable.

The case of the 3D printing industry has triggered visions of transferring the CBPP logic onto the hardware realm. Seeds of such an approach have been observed in grassroots and commons-oriented projects in various domains, from the RepRap project family in 3D printing (Jones et al., 2011); to the L'atelier paysan and Farm Hack initiatives in agriculture (Giotitsas, 2019); the Wikihouse project in construction systems (Priavolou and Niaros, 2019); Wind Empowerment Network in small-scale energy production and Open Bionics in prosthetics (Kostakis et al., 2018); and Sensorica in electronics (Pazaitis, 2019).

Such initiatives exemplify an emerging proto-mode of production, which has been described as "design global, manufacture local" or, in short, "DGML" (Kostakis et al., 2015). Tentative documentation of DGML has demonstrated the innovative capacities of the commons as an alternative path to technological development in response to social needs (Kostakis, 2019; Pantazis and Meyer, 2020), enabling communities to collectively address global challenges, as, for instance, the recent response of open hardware communities to COVID-19 indicated this (Pazaitis et al., 2020; Bowser et al., 2021).

3. The FDM case:

A 3D printing technology in the making

3.1. Motivation and primary observations

Paraphrasing Noble (1984), the history of 3D printing is also the history of politics around the technology. In broad terms, as in other technological advancements, enclosures and patents in 3D printing came to ensure that innovators receive their proper reward (Baker et al., 2017). And yet, communities flourished under frugal conditions, effectuating conditions of low-cost replication for the technology. The

FDM case reveals that innovations are not a direct rationalization of the market alone.

Collective and individual imaginaries and contributions aggregate in shaping innovation in a specific context, and connection to society's aspirations often creates a chasm between a good trajectory, as in "good life," from one that is profitable. Therefore, it is legitimate to closely examine the case of 3D printing, from the origins of the technology and its initial development in the late 1980s to the rapid growth of the field after the expiration of key patents in the late 2000s.

We selected FDM technology on two grounds. First, it is today the most popular and widely commercialized 3D printing technology and has set a benchmark for the types of applications and users that are of relevance. Second, the technology was initially developed in the 1980s and was first commercialized in 1992, yet its utilization remained limited throughout the 20 years of patent protection.

In the following graphs, we indicate the interest over time in Google search and Scopus for some of the most broadly used terms that have been associated with the process that today is generally referred to as 3D printing, such as "Additive Manufacturing," "Rapid Manufacturing," "Direct Manufacturing" and "Rapid Prototyping."

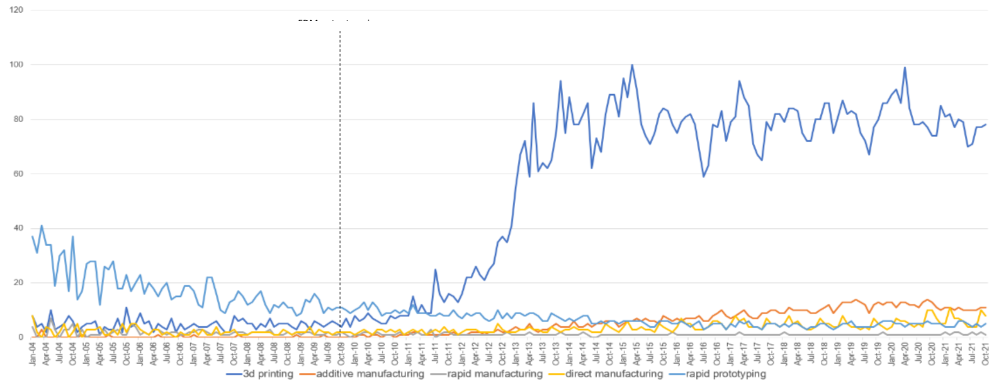

Figure 1: Google Trends results for 3D Printing and related terms from 2004 to 2021 (Source: https://trends.google.com; data edited by authors)

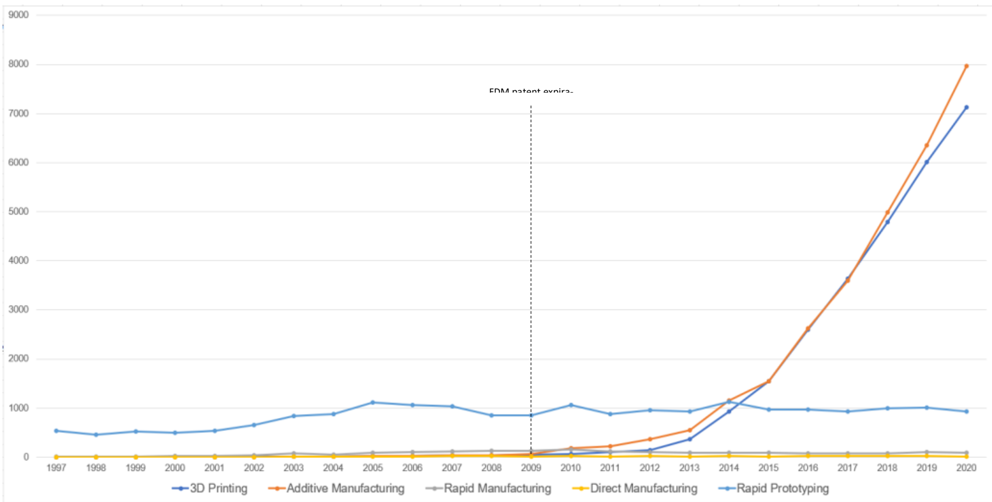

Figure 2: Publications in Scopus mentioning 3D Printing and related terms (Source: Scopus; data edited by authors.)

Two main observations are that: (a) there is a notable gear shift in the years following the FDM patent expiration in both broader public and academia; and (b) "3D printing" seems to be the most widely used term in society, while in academia "Additive Manufacturing" is following a similar trajectory with "3D printing". Further analysis of the subject areas in Scopus indicates that "Additive Manufacturing" is the term largely preferred in STEM fields, while "3D printing" has a broader appearance across different research disciplines. Our exploration of the FDM case concerns the broader socio-technological and cultural phenomenon we henceforth adopt the term "3D printing".

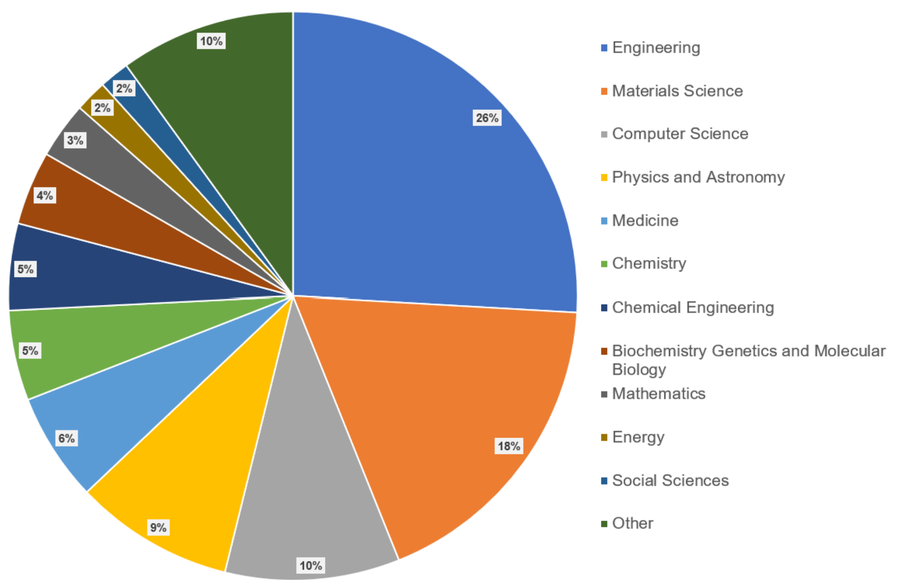

Figure 3: Subject areas of publications in Scopus mentioning the term "3D printing" (Source: Scopus; data edited by authors.)

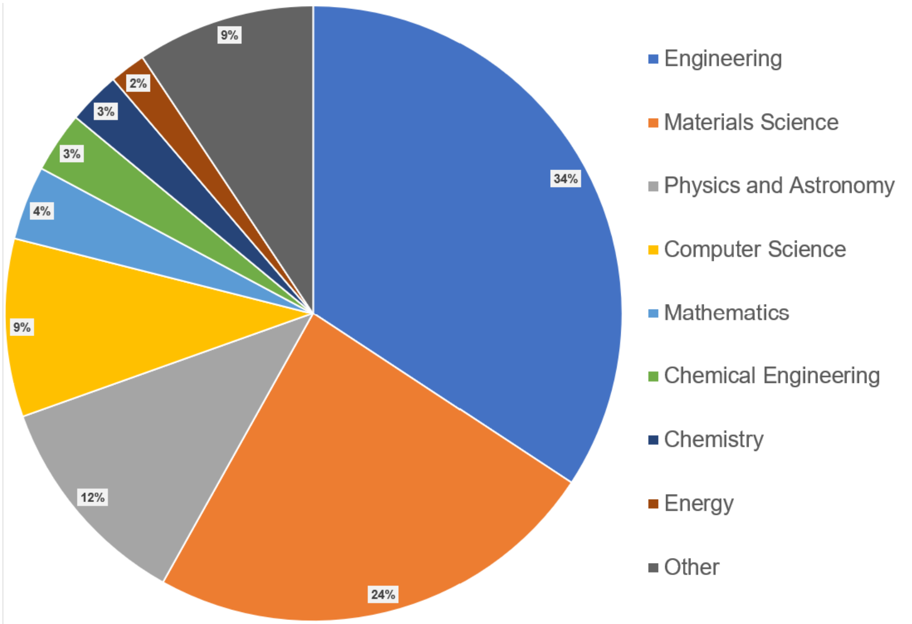

Figure 4: Subject areas of publications in Scopus the term "Additive Manufacturing" (Source: Scopus; data edited by authors.)

After the FDM patent expired in 2009, a growing space of experimentation emerged involving users and small-scale manufacturers that defined new paths of applications and technical improvements. Diverse socio-technical and cultural imaginaries accompanied this process on the technology's potential in revolutionizing manufacturing, industry, and consumption towards more distributed, autonomous, and collaborative forms of production (Anderson, 2012). The current study aspires to encapsulate these heterogeneous aspects in STI policy.

Finally, we should note some practical advantages for selecting the FDM case in particular. The time frame both before and after the patent expiration is adequate for data collection. Current developments indicate that the technology is reaching relative maturity and a dominant design paradigm. Considering the more recent expiration of other patents related to 3D printing (e.g., SLA, SLM, and SLS in 2014), the exploration of the FDM case enables a more nuanced understanding of different technological options available, which may lead to more sustainable and socially meaningful pathways of the technology.

3.2. Materials and methods

We deploy the case study methodology to understand what is important for the examined phenomena within the specified context. The selected case is the FDM technology, used in 3D printing and under patent protection from 1989 to 2009. We build upon the theoretical discussion by analyzing empirical data before and after the patent's expiration to discuss its effect, along with contemporary social and economic developments, on innovation and the development of the industry.

Data is collected from a variety of sources, including relevant research and case studies; reports by industry and market organizations (e.g., Wholers, Sculpteo, IPlytics, IDTech); but also discourse in informal domains, such as community blogs, commentaries, wikis, and news outlets that are representative of the tech-savvy consensus contemporary to the various events we examine in our analysis. We have used tools such as google trends to indicate broader social impact and compared them with respective searches in the Scopus database. Moreover, data is collected from patents' reviews and the concerned companies' public financial information. The data have been qualitatively analyzed and assessed in the context of the theoretical background and interpretation of the observed phenomena.

3.3. Historical development of 3D printing technology

To understand the state of 3D printing today, it is vital to track its origins and how it grew from an industrial to a cultural phenomenon. The evolution of 3D printing technology coincides with an amalgam of breakthroughs in various fields within the industrial paradigm, brought about by the ICT revolution and the relevant changes in the political economy and structural transformations in the global economic environment. We observe the technological development of 3D printing occurred in three waves: (a) the initial period of experimentation and articulation of the concept from prior technologies in the early 1960s; (b) the first commercial applications and emergence of multiple 3D printing methods between 1984 and 2009; and, after that, (c) broad adoption of the technologies by the "maker movement" (Anderson, 2012) giving rise to a consumer boom for 3D printers.

The first period was a capital-intensive, enclosed, and formal research-oriented undertaking, first conceived in the Cold War laboratories of the Battelle Memorial Institute (Wohlers and Gornet, 2014), in close collaboration with academia and industry. The idea of 3D printing is to build solid objects by depositing successive layers of material on top of each other, rather than molding or subtracting material (Bechtold, 2016). During the 1960s, the initial focus was to develop a technology that uses photopolymers to create solid objects from light-sensitive materials. These attempts were, in turn, also based on various incremental breakthroughs taking place during the 1950s, including experimentations with light-sensitive materials by DuPont chemicals and a series of methods for imprinting thermoplastic objects developed by Munz (1956; 1968) referred to as "photo-glyph.

Photo-glyph paved the way for the emergent techniques that came to shape what is today understood as 3D printing, including "photographic-printing process" (Edward, 1919); "radio echo system for mapping contours" (Holser, 1952); and "making models in relief in gelatine by photographic processes" (Frank, 1954). The historical timeline shows how, despite concept and theory having been formulated and proved, the technology proper had to await the invention and availability of yet undeveloped components before it could be effectively actualized.

In the 1980s, the first commercial applications of 3D printing technology emerged, with the methods of "stereo-lithography" (Hull, 1984), later commercialized by 3D Systems; the originally named "three-dimensional printing" by MIT researchers (Sachs et al., 1993); and FDM (Crump, 1992), granted on 30 October 1989 to Scott Crump, later co-founder of Stratasys. The first FDM 3D printer, the 3D Modeler, was introduced by Stratasys in 1992 to challenge the market leader 3D Systems and its stereolithography-based printers. Competition at the time mainly concerned industrial contracts as broader paths of commercialization were yet to be found.

The commercial breakthroughs developed in the 1980s were based on methods and R&D that took place in the previous decades. The National Science Foundation (NSF) in the USA played a crucial role in funding both the precursor technologies that helped pave the way, as well as the development of 3D printing from concept to technological reality (Weber et al., 2013). The precursors of 3D printing technologies developed in the 1970s, such as computer numerical controlled machining and solid modelling tools, were NSF-funded projects. Likewise, NSF supported turning early 3D printing patents in the 1980s into proofs-of-concept and prototype machines in two major commercial technology areas, namely binder jetting and laser sintering. In subsequent years the NSF also funded application development (e.g., medical) and academically-oriented networking activities. More recently, as the technology has matured, the NSF has supported research efforts related to new processes, new applications for existing processes, and benchmarking and road-mapping activities (Weber et al., 2013).

The development timeline of 3D printing indicates the heterogeneity of factors and motivations that contributed to the development and early commercialization of the technology. It testifies to the evolutionary view of innovation that combines diverse inputs from both public and private agents within a broader socio-technological context.

3.4. The FDM patent expiration and the nascent political economy of consumer 3D printing

With the FDM patent approaching expiration, Adrian Bowyer, an engineer from Bath University, began creating RepRap (short for Replicating Rapid prototyper): the first open-source, self-replicating 3D printing machine. At that stage of its development, the market for 3D printing was growing. Still, the performance of FDM machines in terms of speed and accuracy constrained the prospects for its use in the industry and posed challenges for those trying to advance further development. The technology was not in great demand for commercial 3D printing activities at the outset either.

This began to change during the 2010s. Despite early experiments and research by national science institutes (Weber et al., 2013), it was left to small start-ups to commercialize the technology. Like the personal computer industry before, 3D printing needed a qualitative breakthrough to enter the mainstream. 3D printing could become a consumer electronic device (never intended in early stages) or a production technology. With the RepRap model, low-cost 3D printers began to spring up, giving a significant boost to the spreading of the technology and helping generate more capital flow into emerging markets for 3D printing.

RepRap tapped into an emerging mode of production that was, at the time, primarily associated with the digital sphere, namely commons-based peer production (CBPP) (Benkler, 200; 2006). Harnessing a long tail of smaller and larger contributions by dispersed communities on a global level in a coherent collaborative relation, open-source RepRap managed to solve the bottlenecks that impeded the expansion of a consumer 3D printing market. In a matter of a few years, a vibrant market was created along with a distinct commons-based innovation ecosystem comprising communities of open hardware enthusiasts, FOSS developers, service providers, and funding instruments (Bechtold, 2016). The cost of a 3D printer dropped within a few years from roughly 100.000 USD to a few thousands, with RepRap do-it-yourself kits made available for a few hundreds[1].

Open-source 3D printing communities co-developed all the necessary building blocks for innovation based on diverse motivations, often not including (direct) financial compensation or foreseen returns. They shared designs that solved technical issues or improved

[1] https://www.economist.com/babbage/2012/09/09/difference-engine-the-pc-all-over-again.

performance, while collaborative platforms were developed to share ideas and user-generated design files for potential objects that could be printed or other applications (Bechtold, 2016; West and Kuk, 2016). Physical spaces, such as Fab Labs or Makerspaces, providing access to 3D printing technologies began to appear and became grounds for rapid learning and experimentation. A political economy emerged where the lines between producers and consumers were blurred, and productive forces responded directly to social signals and the needs of user communities.

One of the first commercial success stories of open-source 3D printers is MakerBot, which went from a hangout to a company that in 2011 received $10 million in venture capital (Feld, 2011). By 2013 MakerBot was valued at more than $400 million at the time that it was acquired by industry leader Stratasys, which saw a significant market opening for desktop 3D printers (Etherington, 2013). For a time, MakerBot was very popular both in the tech industry and the open hardware movement. It was viewed by the former as evidence for the highly innovative character of the start-up model and the latter as a successful open hardware project, which emerged from the community and was growing symbiotically.

Yet this symbiosis did not last for long. After being acquired by Stratasys, MakerBot struggled to balance contradictory interests between investors and its user community until eventually giving in to the pressures of the former. This was signified by the replacement of its co-founder Bre Pettis in the CEO position, followed by the restriction of parts of its new technologies (Brown, 2012) and by the rebranding and tighter control over its community platform Thingiverse (West & Kuk, 2016).

For parent company Stratasys, the impact of the MakerBot acquisition and enclosure has been noteworthy in terms of its market performance. According to Stratasys' annual financial report in 2014, MakerBot sold nearly 40,000 3D printing systems, which accounted for almost 86% of the Stratasys net sales during that year (Stratasys, 2015). However, in 2015 the respective units sold by MakerBot dropped to 18,673 (Stratasys, 2016), while in 2016, Stratasys acknowledged a substantial drop in sales and revenues, seeing the profit margin in the entry-level systems like MakerBot rapidly squeezed, and consequently implemented cost cuts (Stratasys, 2017).

MakerBot was facing community outrage due to the concealing of essential features of the machine, such as a nozzle part, which only became worse when the company sought to file a patent for a smart extruder that was mainly developed through the efforts of the user community (Benchoff, 2014). MakerBot attempted to maintain the support of a global community of users by claiming that restricting certain aspects and parts of its machines would allow it to continue production in its headquarters in Brooklyn, maintaining local jobs. However, in 2015 MakerBot implemented massive layoffs (O'Kane, 2015; Pearson, 2015), and, eventually, in April 2016, it closed down its central manufacturing facility in Brooklyn to move its operations to China (Heller, 2016).

The cautionary tale of MakerBot illustrates its failure to formulate a business model which would guarantee profitability while maintaining the vibrant community spirit and engagement that has driven innovation in the field. Other companies stepped in to engage with the community and have followed different paths, further analysis of which exceeds the confines of this paper. Still, the incongruences exhibited in the case of MakerBot largely remain and the hybrid models employed by other open-source 3D printing companies to maintain openness face difficulties ensuring long-term financial sustainability for the companies that use them. The development of flexible IPRs which would make this conjunction possible seems imperative.

4. Discussion: Beyond open and closed technology

4.1. Patent matters in open-source 3D printing

A direct causal relationship between the patent expiration and the development of open-source 3D printing relies on anecdotal evidence as it is seemingly difficult to empirically show such a direct correlation (Bechtold, 2016). Admittedly, Bowyer started experimenting with FDM technologies a few years before the patent expiration, attesting to the argument that patents do not stop people from experimenting in garages and other informal spaces, outside production sites, and the market (Kurman and Lipson, 2013).

Nevertheless, the absence of legal barriers arguably enhanced the prospects of experimentation. It accelerated the widespread use of the technology by universities, makers, hackerspaces, and grassroots communities, seeking to develop and improve the process during the first decade of the 21st century, which opened up different paths of commercialization. Simultaneously, an accompanying ecosystem of open-source 3D printers, comprising open-source software and designs, and open, physical, and digital spaces of learning, knowledge and technology sharing was crucial to the development of the innovation ecosystem and was both contingent to- and inspired by the open-source mindset and culture (Bechtold, 2016). Even if patents were technically not prohibiting experimentation, they still conveyed a socio-institutional logic based on technological appropriation and knowledge commodification that necessitated a paradigm shift in the way society has agency in technological development.

Hence, the leap in the development of open-source 3D printers is not strictly a technical endeavor, but most importantly, a political one. Narratives inspired by 3D printing predominantly encourage individuals and small groups of people to use the machines to serve their immediate needs. Power in this kind of politics is associated with access to technology rather than distinctive political assertions. Thus patents, representing barriers to entry, are seen as the enemy. The corporate world, primarily associated with patents and rent-seeking behavior, is considered by communities as stealing from the pool of shared resources that small groups and individuals create.

Users of 3D printing have the freedom to venture down the paths of innovation via bypassing legal constraints. Productive relations in "makerspaces" or "hackerspaces" hover between labor and recreation, while significant value is produced for local communities, along with great learning and innovation potential and participatory visions of governance (Niaros et al., 2017). The broad diffusion of the Internet facilitated these small-group dynamics to scale globally. The popularization of the technology and its growing use by hobbyists and activists brought along an upsurge of research on the impact of sharing platforms, such as Thingiverse (Claussen and Halbinger, 2021) and user-driven innovation or household sector innovation (Von Hippel, 2005; 2017).

The same transformative potential sparked discussion around 3D printing and IPRs (Hornick and Roland, 2013; Mendis, 2013; Peacock,

2014) concerning both the technology and its 3D outputs (Wilkof, 2016). The prospects of low-cost 3D printing raised concerns on presumptive "digital patent infringement" (Holbrook and Osborn, 2014). Like digital file-sharing disrupted the music and video industries, so would 3D printing challenge patents for physical objects through the sharing of CAD files. Moreover, even when IPR rules can be clarified in such situations, their enforcement would be challenging (Bechtold, 2015; Birtchnell et al., 2018). However, recent reports indicate that such occasions of infringement appear, for now, to be a matter of theoretical discussion rather than a pressing need for legal reform (Birtchnell et al., 2018). Yet, such concerns could still invoke real legal implications, further constraining online sharing practices, similar to Articles 11 and 13 of the EU copyright directive (EC, 2016), as a 2018 Resolution of the European Parliament suggests (EP, 2018).

The role of patents in 3D printing is ambivalent. The development of open-source 3D printers is based on technological advancements led by industrial manufacturers, in which patents played a significant role. Yet open-source 3D printers and their accompanying ecosystem demonstrated novel combinations of 3D printing methods with forms of communication and collaboration effectuated by digital media, which paved the way for expanding the consumer 3D printing market (Bechtold, 2016).

Therefore, it is impossible to quantify the contribution of patents or open-source practices to the development of the technology – and trying to do so may already be in the wrong direction (Pazaitis and Kostakis, 2021). Yet, it is essential to acknowledge the diverse social and cultural phenomena that emerged after the patent expiration, which defined pathways that were not foreseen before. Openness played a substantial role in developing the technology (Bechtold, 2015; Birtchnell et al., 2018) but raises serious concerns around the transformations the emerging socio-technical systems spawn, which IPRs rules seem unable to address.

Open-source 3D printing was able to develop through various factors coming together in the technological, social and political fields to eventually define the fate of 3D printing in the economy and society. FDM exhibited specific technological capabilities, but they alone did not determine any particular trajectory. The social and cultural context to which future 3D printing manufacturers responded were co-created by a broad community of users and agents driven by diverse motivations, eventually defining the route to commercialization and uptake. Our argument is thus that patent expiration was one important event that allowed other factors to come together into a multifaceted phenomenon. Hence, it is vital to understand and identify the conditions that can enable such conditions to occur in the future, steering them where most needed, along with viable economic models that may sustain their workings in the long term.

4.1. The new enclosures in 3D printing technology

After the expiration of key patents in the 2010s and the adoption of the technology in both consumer and industrial settings, more than 14,000 patent applications mentioning the FDM method have been filed by the end of 2020, formulating a new environment of enclosures in 3D printing. Of these, the primary owners, including both manufacturers and users of the technology, are some of the most prominent players in the game: Stratasys Inc, General Electric, 3D systems, Boeing Co, and several others.

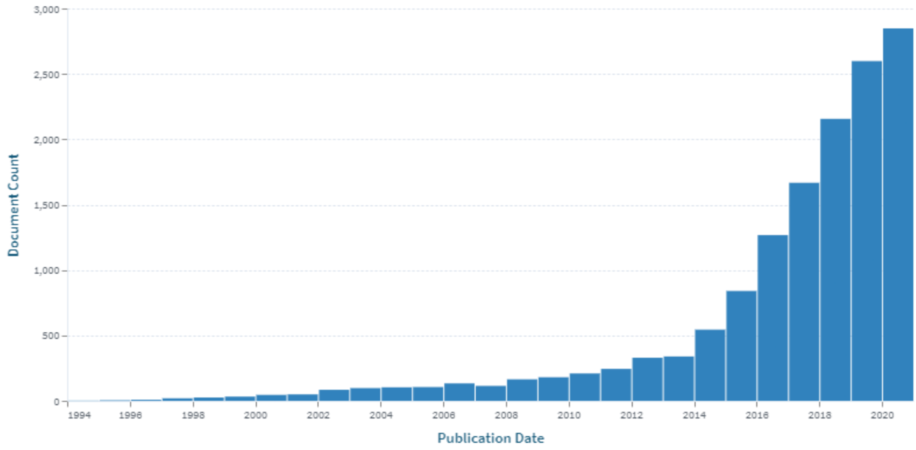

Figure 7: Patent documents over time mentioning Fused Deposition Modeling (Source: Lens.org. Available at: https://link.lens.org/yy8Lhfe9mhf.)

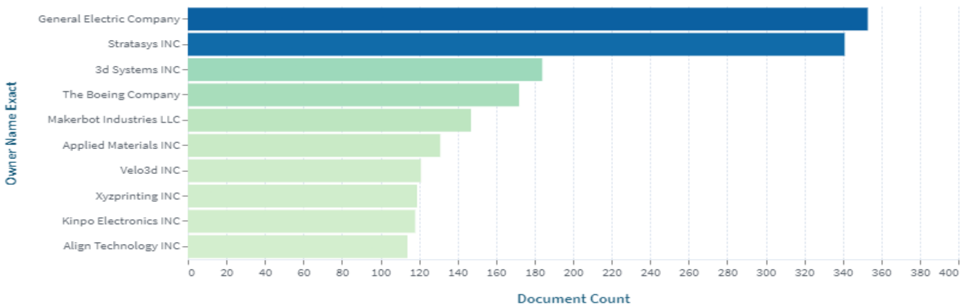

Figure 8: Top owners for patent documents mentioning Fused Deposition Modeling (Source: Lens.org. Available at: https://link.lens.org/yy8Lhfe9mhf).

According to the 2019 IPlytics report on the 3D printing industry, the increasing trend for FDM patents is followed by other 3D printing technologies. There is a sharp increase in patent filings, while similar intensity is also evident in the number of patent litigations (155 from 2007 to 2018 in the US alone), with future 3D printing technologies expected to rely on patents heavily.

As the tendency of the market is expected to further grow at a pace exceeding 14% compound annual growth rate from 2020 to 2027, the growth of the industrial applications forges ahead of desktop 3D printing, with 77% of market share in 2019 (Grand View Research, 2020). Nevertheless, desktop 3D printing and community manufacturing remain a considerable aspect due to their ability to disrupt several industries, such as the toy and game market (ibid).

The IPRs system is a big players club aiming to secure profits. As collateral damage to this commercialization process, communities are in danger of losing an environment of openness, and new barriers to innovation are introduced. The extensive patenting is indicative of the profitability prospects in a dynamic and diversified market for 3D printers, which has been effectuated, inter alia, by broad community experimentation and a diverse socio-technological context following the diffusion of digital technologies, as also reported by a 2015 WIPO study (Bechtold, 2015). These developments indicate a recurrence towards a direction resembling the situation before the patent expiration. The market structure tends to become more consolidated, and the industrial trajectories are favored over the consumer ones.

Even as openness contributed to the development of 3D printing technology and the creation of a dynamic market, market growth seems to invariably involve patents as a fundamental tool. This contradiction requires a deeper understanding of openness as a trajectory of technological advance and innovation.

4.2. The ambivalence of openness

The issue of openness has been puzzling STI scholarship and practice due to its ambivalence and inherent contradictions (Dahlander and Gann, 2001). Open innovation has been recognized as a new innovation paradigm contrasted to vertical R&D (Chesbrough, 2003; 2006; 2008), but several conflicting elements remain. First, openness is often viewed as a paradox in profiting from innovation, conventionally linked to appropriability and control (Laursen and Salter, 2014). Second, systematic analysis of dimensions of openness in incumbent firms and industries has shifted away from early perceptions of openness towards interpretations of the "contingencies under which it makes sense to be open" (Dahlander et al., 2021, p.8).

Eventually, this conceptual shift impelled by the contradictions of openness in innovation literature has led to views of openness as a strategic option to manage external knowledge flows. The case of MakerBot and the company's clash with its user community in Thingiverse has itself been analyzed as a way to integrate complementary assets (West and Kuk, 2016) or pre-innovation platform activity to increase diffusion (Claussen and Halbinger, 2021). However, in all their nuance and incrementality, such approaches beg the question of how "open" innovation in the dominant perception is and whether the concept of openness eventually brings anything new at all in conceptualizing innovation. Current approaches arguably fail to understand and explain unique pathways of organizing innovative capacities in conditions of openness (Pazaitis, 2020).

There are qualities and degrees of openness in the story of 3D printing technology that exceeds the mere existence of IPR. Amidst emerging techno-social conditions driven by digital technologies, RepRap devised an innovation strategy that effectively mobilized rich motivational diversity from different agents. An open process that was purposive and proactive rather than strategic or coincidental and not primarily driven by financial returns has produced significant improvements in design, operations, organization, and market paths, more effectively than strategies that have long been considered the norm.

Moreover, the open-source practices that emerged around 3D printing have stimulated a series of significant organizational and institutional innovations, which have been shown to incite visions of alternative systems of production and technological design. Such practices may hold critical insights for developing an institutional framework for innovation that might better serve societal needs, especially given humanity's current grand challenges.

4.3. Towards a commons-based innovation framework

The dimensions of openness demonstrated in cases like FDM were inspired by the salient success of innovations from commons-based peer production (CBPP) projects like Wikipedia and FOSS. CBPP has been shown how a rich diversity of motives, not limited to financial ones, can be mobilized in mass through social signals, based on open collaboration and shared resources (Benkler, 2001; 2006; Bauwens et al., 2019). The economic success, but also the meaningful social relations stemming from CBPP, have sparked collective imaginaries that found physical manifestations through the RepRap project.

Parallel to the more commercially oriented cases like MakerBot, the same imaginaries were manifested in projects oriented towards social impact. The potential of such configurations has been documented in various domains, such as prosthetics (Kostakis et al., 2018); construction and housing (Priavolou and Niaros, 2019; Priavolou et al., 2021); small-scale wind turbines (Latoufis et al., 2015; Robra et al., 2021);

agricultural machines (Giotitsas 2019; Pantazis and Meyer, 2020; Kostakis et al., 2021); or emergency response in the context of the COVID-19 pandemic (Pazaitis et al., 2020; Bowser et al., 2021).

Such cases examined under the lens of "design global, manufacture local" (in short DGML; Kostakis et al., 2015) encapsulate innovation features that cast the FDM case's story in a different light. These features go beyond openness, seen as the mere absence of legal barriers of access to knowledge and technology. Instead, they demonstrate specific organizational and productive configurations that can be better grasped under a more clear-cut framework, namely that of commons-based innovation (Coriat, 2015; Pazaitis, 2020; Pazaitis et al., 2021). DGML cases already indicate preliminary institutions of a commons-based innovation framework that may better serve societal needs.

Unlike the industrial logic of exploiting tight IPR and global supply chains for massive economies of scale, DGML promotes global access to industrial knowledge and localized physical construction. Design of technologies and products may take place collaboratively on a global scale. In contrast, manufacturing takes place locally, adapted to specific needs and preferences, with the assistance of small-scale fabrication technologies. A commons-based institutional framework for innovation could enable communities to produce better and more socially relevant technology while unlocking path dependencies that hinder our efforts to address contemporary challenges, such as the climate emergency.

But, despite the concurrence of specific techno-social dynamics in the emergence of the DGML phenomenon, its eventual outcomes are neither technologically determined nor expected to be rational choices of the market (Pazaitis and Kostakis, 2021). As Dosi et al. (2019) emphasize, institutions are not mere configurations of efficiency spawned by individual rationality but path-dependent social arrangements co-evolving alongside cumulative organizational patterns on different levels.

The FDM case unveils numerous layers of tension with the current institutional framework. Property-based legal and economic arrangements failed to acknowledge and support a cluster of socio-economic practices that could benefit both innovators and society. The monolithic focus of IPR on mass-scale and centralized appropriation of knowledge and technology could not adequately cover a participatory innovation process that defined the course of a low-cost 3D printing industry. The viability of such practices is less a matter of how a single firm, or innovator, may profit from innovation and more a matter of how the economy as a whole may progress (Nelson, 2006). Hence, an alternative trajectory would require a substantial number of firms aligning with what seems to best serve the public interest, which IPRs have empirically been shown to not achieve.

These limitations of IPR emphasize the need for an alternative yet clearly defined framework. Following Bollier's (2014) interpretation of commoning, the institutional arrangements in a commons-based innovation regime define participation and knowledge sharing across the economy by regulating the relations among (a) the common pool of resources; (b) the community of agents contributing to- and benefiting from it; and (c) the rules, norms, and social practices under which the latter takes place. Entrepreneurial ventures could better design their commercialization paths by organizing commoning capacities in reciprocity to the above rules to better serve the community as a whole. Hybrid or reciprocity-based license forms (Bauwens et al., 2019) could protect the commons from external predatory attempts threatening the sustainability of the ecosystem.

Finally, a commons-based IPR regime aims at institutional diversity, which departs from the current colonial-type of regime. Yet, commons-based entrepreneurial practices have often been shown to beget their own demise as they become successful (Allen and Potts, 2016), which speaks for the incompatibility with proprietary forms of innovation in the long term. Hence, such symbiosis with current institutions, such as patents and copyright, or trade barriers, may only be helpful to the extent that it facilitates the long-term transition. Alternative and distributed forms of finance for innovation would also be vital in decoupling technological advance from the imperatives of growth and accumulation that impedes commoning activity.

It has been previously illustrated that the state has a crucial role in this process (Pazaitis and Drechsler, 2021). The importance of mission-oriented public investments has been extensively documented in paving the way for markets to crowd in innovation (Kattel and Mazzucato, 2018). Likewise, public investments in shared infrastructures, such as local makerspaces and digital platforms for shared knowledge and design like Thingiverse, along with the definition of appropriate legal arrangements, can open the way for commons-based forms of crowding in.

There is, admittedly, an endless list of limitations and challenges concerning the mechanics of this transformation. Yet, the purpose of this paper is not to address them, as it is seemingly impossible at this point. Instead, it is to open a critical and inclusive discussion among scholars and practitioners to begin delineating the way towards better technology for society. This path is steep but inevitable if we are to surpass humanity's greatest challenges.

5. Conclusions

In this paper, we attempted to raise critical insights concerning the role of patents in innovation and discuss their limitations and viable alternative pathways. With the well-established arguments against patents as a starting point, we explored the case of 3D printing, a technology that rapidly developed after the expiration of key patents. We analyzed how the patent expiration for the FDM technology, broadly utilized in 3D printing, coincided with a dynamic synergy among diverse communities harnessing the digital revolution to establish new commercial paths and a vibrant market.

Exemplar open design projects, such as RepRap, inspired by commons-based practices, such as free and open-source software and Wikipedia, managed to pull together diverse creative capacities, which conventional industrial methods were seemingly unable to spawn. A lively community coalesced around the technology through broad experimentation, improving and developing its technical components, along with the relevant organizational practices and learning in shared spaces, like Fab Labs and Makerspaces. This process spurred new innovative ventures like MakerBot that quickly elicited rapid market growth while maintaining an open-source profile.

However, this did not last long. Under immense structural pressures and intensifying market competition, MakerBot was forced to gradually close its technology, including new components, among other things, co-developed by its user community. Losing community support and engagement came with the cost of a reduced user/developer base leading to massive losses in market share, extensive downsizing, and layoffs. Other companies with an open-source profile took over, yet the challenges of this business model remain unresolved.

The role of patents in 3D printing technology remains ambivalent. Recent developments of extensive patenting in 3D printing indicate a recurrence towards proprietary innovation pathways. In this light, we discussed how openness as a condition fueling technological advance challenges innovation scholarship, as it alone seems to be incompatible with sustained market operation. Drawing lessons from paradigmatic commons-based projects in various domains, we formulated proposals for an alternative framework for innovation, building on global digital commons of knowledge, software and design, and local shared manufacturing capacities. Further exploration of such a framework may unveil the potential of emerging pathways of research and practice around more fair and sustainable innovation that could better serve societal needs and help address global challenges, such as the climate emergency.

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