Paper to be presented at: DRUID17
NYU Stern School of Business, New York, June 12-14, 2017

Finding the Path to Disruption in 3D Printing: How Technology Frames Shape Disruptors’ Choices

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Abstract
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developed by firms, to help understand whether innovations become disruptive and what drives heterogeneity in firm performance.
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ABSTRACT
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Keywords:
3D printing, Disruptive Innovation, Industry Emergence, Technical Change, Technology Frames
INTRODUCTION

Many new technologies have the potential to disrupt established approaches—but relatively few actually do so. Historians of technologies have extensively discussed, for example, long waves of economic development that build on broad, pervasive technologies to generate new paradigms of production and consumption (e.g. Freeman & Louça, 2001). They have identified a few characteristics (e.g. pervasiveness of applications) that, in the long term, lead to the emergence of new industries and leaders. Yet, without the benefit of hindsight, managers and strategy scholars alike still struggle to predict which technologies will deliver truly disruptive effects, or say how to benefit from them before they become established.

In this paper, we look at the factors driving the evolution of 3D printing. We examine the three leading firms that have developed 3D printing technologies over the past 30 years, and their interaction with user industries and lead clients. We analyze the evolution of their strategies in response to both internal developments (endogenous factors) and external events (exogenous factors). We observe heterogeneity among our candidate disruptors in terms of technologies they develop, their product design choices and, finally, the building blocks of their business models.

To make sense of how these firms’ choices evolve in different, yet internally consistent ways, we leverage the discussion on the evolution of complex socio-technical systems (e.g. Garud & Rappa, 1994). More specifically, we rely on the concept of technology frames (Orlikowski & Gash, 1994; Kaplan & Tripsas, 2008; Kaplan, 2008).

Technology frames are “collectively constructed sets of assumptions, knowledge and expectations regarding a technology and its uses and applications in organizations” (defined in Cornelissen & Werner, 2014, p. 185, based on Orlikowski & Gash, 1994; Kaplan & Tripsas, 2008). We look at how different frames emerged and evolved in the 3D printing industry. This is important, because accounts of disruption have mostly focused on technology and market
characteristics to explain how disruptive innovations enter industries and displace incumbents (e.g. Christensen, 1997; Adner, 2002). However, such accounts leave little room for the inherent uncertainty and ambiguity surrounding new technologies (e.g. Santos & Eisenhardt, 2009). When a new technology is born, its implications are far from clear to either incumbents or innovators. Different firms will “bet” on different options? Their choices will have long-lasting effects on the evolution and impact of the technology itself, as they are embedded in routines, processes, and decision-making criteria (Nelson & Winter, 1982; Garud & Rappa, 1994).

Consequently, understanding firms’ choices is crucial to explain their own performance, but also the overall impact of the “disruptive” technology they focus on. We argue that, by taking the viewpoint of the (would-be) disruptor, we can extend the discussion on disruptive innovations, as the issue of firm choice has been largely overlooked by past research—Ansari, Garud, & Kumaraswamy (2016) and Ansari & Krop (2012) being exceptions. In particular, Ansari et al. (2016) find that disruptors need to compete and cooperate with the very incumbents they wish to displace. They describe disruptors’ strategies as guided by either a sustaining or a disruptive frame. What remains to be understood is how, on the technology or industry level, firms come to understand the disruptive potential of a technology, and what options it gives them.

We build upon and extend this work, focusing on the evolution of technological frames in an emerging industry. Technology frames impact not only the technology trajectory pursued (Garud & Rappa, 1994; Kaplan & Tripsas, 2008), but also the product design choices made by innovating firms (Leonardi, 2011; Benner & Tripsas, 2012) and firm positioning and business models (e.g. Rosa, Porac, Runser-Spanjol, & Saxon, 1999; Anthony, Nelson & Tripsas, 2016). The challenge of disruption is how to introduce technologies to industries with which they are not immediately compatible. Frames guide firms’ choices in their effort to bridge the gap between perceived technological opportunities and actual applications.
In the early days of a new technology, technology frames are in constant flux, as technologies and market opportunities develop. Yet, they also exhibit a degree of convergence, aligning industry actors around a common understanding of the technology and its value in application (Kaplan & Tripsas, 2008). This tension between convergence and evolution lies at the heart of the process of disruption. To better understand how firms can successfully turn inherently uncertain technologies into disruptions, we thus need to understand: How do the technology frames of innovating firms evolve over time? And in response to which factors?

We trace the technology frames of the three leading 3D printing OEMs, focusing on the transition from rapid prototyping to direct manufacturing. Our approach differs from previous studies, which focused on the tensions between a single disruptor and the disrupted, thus neglecting the influence of competitive dynamics among firms in the process of defining their market. We trace changes in the OEMs’ frames over time in response to both internal developments and competitive dynamics, and their influence on the structure of the industry.

We find that, after initial convergence, the frames of the three main OEMs began to diverge when a new 3D-printed product was manufactured on an industrial scale by a client firm for the first time. This “exogenous shock” kick-started discussion on the transition of 3D printing applications from prototyping to manufacturing. OEMs’ responses varied. They found it hard to move out of the frame they had initially formed, and were inclined to bend this existing frame to the new situation rather than fundamentally transform it. The most important point of incompatibility between the initial frame and disruptive applications was the locus of control over the technology. As the OEMs, to varying extents, resisted change, new firms entered the industry, generating a new wave of competition based on rather different frames.

Our findings show that the technology frames of disruptors are indeed a decisive factor in how their innovations come to impact existing industries. The focus on innovators’ technology
frames contributes to the understanding of disruptive innovation in at least two ways, explaining whether a new technology becomes disruptive and which firms achieve disruption. First, it sheds light on disruption as an uncertain process, rather than a predetermined outcome of innovation (Christensen, 2006; Ansari et al., 2016). Whether an innovation ends up disrupting existing industries largely depends on how innovating firms frame it. This implication resonates with and further develops a surging field of research on the sociocognitive role of firms in shaping industrial change (e.g. Ozcan & Santos, 2015; Grodal, Gotsopoulos, & Suarez, 2015; Bingham & Kahl, 2013). Second, the technology-frame lens shows why firms developing the same underlying technology end up in different market segments and different roles. Within firms, technology frames provide the domain for strategic choices, as well as reactions to environmental change (Kaplan, 2008). As we study this process on an industry level, we observe that technology frames shape the paths of innovations and the firms that advocate them.

THEORETICAL BACKGROUND

Firms in new industries have considerable influence in shaping their environments (Santos & Eisenhardt, 2009) and are flexible in how they bring products to market (Murray & Tripsas, 2004; Kerr, Nanda, & Rhodes-Kropf, 2014). Yet, flexibility is a mixed blessing when there is no past experience to provide a reliable baseline for decisions.

In particular, firms dealing with potentially disruptive innovations face challenges related to, on the one hand, identifying a suitable application for their innovation when this application does not yet exist, and on the other hand connecting with customers and other industry actors for whom the innovation is not advantageous, at least in the short run, and may even be competence-destroying (e.g. Abernathy & Clark, 1985; Adner, 2002; Ansari et al., 2016).
New firms must learn and experiment, with technology but also with positioning choices, organizational structures, business models, and overall strategy. Lacking clearly defined paths, firms rely on assumptions about the technology and its possible use to set a course.

Such sets of ideas and assumptions have been studied as technology frames (Orlikowski & Gash, 1994), “collectively constructed sets of assumptions, knowledge and expectations regarding a technology and its uses and applications in organizations” (Cornelissen & Werner, 2014, p.184). On a broad level, they are related to strategic frames: “cognitive representations of firms in an industry, including assumptions of capabilities and bases of competition” (Cornelissen & Werner, 2014, p. 184; Nadkarni & Narayanan, 2007; Kaplan, 2008).

Technology frames have been studied as mechanisms of cognitive representation, applied to technology (Orlikowski & Gash, 1994; in this field, “frames” are also dubbed “cognitive maps,” “dominant logics,” and “schemas,” among other terms—see Walsh, 1995 for an overview). The perspective has two intellectual roots. The first is the observation of industries as cognitive communities of actors with collectively held perceptions about competitors and competitive dynamics (Porac et al., 1989; Spender, 1989). The second is the realization that technologies are uncertain and undefined by nature: Their meaning, use, and value are socially constructed (Bijker, Hughes, & Pinch, 1987). This idea has been incorporated into the literature on technology frames as “technology beliefs” (Garud & Rappa, 1994).

The impact of technology frames or beliefs has been identified on different levels of industrial development, from the evaluation and use of a new technology in a single firm (Orlikowski & Gash, 1994) to the selection between rival technological alternatives in a new industry (Garud & Rappa, 1994). At the core lies the notion that actors (individuals or, in aggregated form, firms) hold a technology frame regarding a (new) technology. This frame consequently directs their attention (Weick, 1979), thereby creating a domain for the further
definition of the new technology and its applications. Their decisions both guide and constrain the development of technology frames. This, in turn, determines how firms bridge the gap between perceived technological opportunities and actual applications.

To understand how firms set themselves up to achieve their goals, we must, therefore, understand the technology frames that underpin their assumptions and expectations and guide their decisions. Three dimensions of firm choices in early-stage industries can be distinguished: technology, product, and business-model (Murray & Tripsas, 2004). These correspond to different aspects of a technological frame: the nature of the technology, its applicability, and its value. Accordingly, we should expect the choices of firms on these different levels to be shaped by the technology frame—see Figure 1. Below, we uncover the process through which innovating firms’ choices interact in technological frames and affect how disruption takes place.

CONTEXT AND METHODS

The 3D printing industry

Our context for this study is the 3D printing industry. First developed in the mid-1980s, 3D printing has many potential and actual applications in industries such as automotive, aerospace, and engineering, and clients in these sectors are still the most important for the OEMs who develop and supply 3D printers. It has predominantly been used in two main areas: prototyping and direct manufacturing on an industrial scale.

3D printing for prototyping is a relatively straightforward application. It can be adopted at relatively little cost, with limited organizational implications, to replace the laborious process of building prototypes by hand (e.g. Gibson, Rosen, & Stucker, 2006; Hopkinson, Hague, &
Dickens, 2006). Firms can reduce the time between design and testing, and also produce multiple variants of parts, allowing them to speed up the product-development process.

3D printing for direct manufacturing, on the other hand, potentially has much more unpredictable effects. For example, General Electric is using 3D printing to slash the number of parts in its next-generation airplane engines, while reducing their weight and enhancing their performance. The main advantages of 3D printing lie in different cost structures (e.g. fixed costs mostly become variable costs), different design rules (e.g. no cost penalty for part complexity, more freedom in geometries), and different value-creation opportunities (e.g. in customization, producing spare parts on demand). Accordingly, for manufacturing firms, 3D printing provides opportunities for product and productivity improvement, but these come at the cost of having to reorganize around a new process technology, as well as developing a new knowledge base around new material and part properties.

Our study focuses on 3D printing OEMs’ attempts to move from prototyping to direct manufacturing. The fact that 3D printing is such a versatile technology, with different implications for different applications, creates many options for firms to position it as they see fit (Shane, 2000); hence the usefulness of this setting to study the origin of a disruption.

Several other factors make this context valuable for our study. First, the industry was developed and shaped almost exclusively by three firms, which still lead the industry today. These firms, de novo entrants, have passed through comparable phases of industrial development, solving similar problems for similar customers. At the same time, they exhibit heterogeneity in terms of approach. Hence the usefulness of this setting to study the evolution of technological frames. Finally, the development of this industry has been well documented, from the perspective of the firms involved as well as from a technology perspective and industry-wide lenses. This allows us to place firms’ actions and expressions in context, within the industry and over time.
Our study takes the form of a longitudinal, embedded case study, focusing on the three largest firms in the industry over a period of 30 years, from the invention of the 3D printing process around 1985 until 2014 (Yin, 2013; Pettigrew, 1990). This approach allows us to use data from the temporal context. We trace the actions and interpretations of the three firms that have shaped the industry. To understand the link between these firms’ actions and the (potentially) disruptive effects of their technology, it is crucial to include the views of other industry actors at the same time, most importantly the firms that were to adopt the technology. In doing so, we can reconstruct the technology frames these firms held, how these frames shaped their actions, and how they subsequently affected the disruptiveness of 3D printing.

The three firms we study have, so far, been the leading players, in terms of both size and technology leadership. Other relevant entrants can roughly be assigned to three categories: early-stage entrants with similar solutions but different technological alternatives; firms who entered between 2000 and 2010, mostly European, with similar offerings to EOS; and more recent entrants from different directions (de novo, as well as diversifying). This last group of recent entrants have entered based partly on the observation that existing OEMs were failing to bring 3D printing to direct manufacturing, and have opted for very different product designs and business models. This makes them relevant for our study, and therefore we integrate this new-entry pattern in our discussion of industry developments.

**Methods and data**

To get a holistic picture of the 3D printing ecosystem and the evolution of frames over time we used multiple sets of data (archival, technical documentation, and interviews). We complemented this with “appreciative theorizing” (Nelson & Winter, 1982; Cacciatori & Jacobides, 2005). That is, we went through several rounds of iterations between evidence and theory to develop new
insights and understanding into the dynamics of technology frames in the context of disruptive innovation.

We took an inductive approach. First, we combined secondary data in the form of contemporary firm documentation with industry-wide and technological overviews. Additionally, we conducted nine interviews, following the approach of earlier studies in this field (e.g. Ansari et al., 2016; Joseph & Ocasio, 2012). We interviewed actors who were involved in key developments, as well as independent industry experts who could provide a more holistic view. Taken together, our interviewees, all based in the US or Europe, span: the three OEMs of focus; new entrants; customers in the main user industries; and other industry actors. The semi-structured interviews typically lasted 30–60 minutes, and 50 minutes on average.

We employed this wide range of data for two reasons. First, to understand the 3D printing industry from different points of view, and for triangulation (Eisenhardt, 1989). Second, to cover firm behavior in multiple dimensions. The technology-frame construct covers the technology, its application, and the value it can create; assessing it therefore calls for data covering all aspects of firm behavior, embedded in the industrial and temporal context. We collected archival data covering the period 1986–2014. Our interviews combined assessments of the overall state of the industry with historical reflections. Table 1 presents an overview of data sources.

It is important to highlight that during the initial analyses of our interviews we organized the information longitudinally in order to trace firms’ actions and perspectives in context over time. This was crucial for understanding their frames, and also to observe the emergence of three different dimensions of firm choices that varied in importance over time.

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Consistent with our inductive approach, throughout this study we cycled iteratively between in-depth analysis of each firm’s actions, comparison across cases, and connections to the literature. At each step, we consciously looked for potential puzzles that could take us to the next step in our analysis and theorizing (Agar 1986). As a consequence, both our research questions and our findings evolved over time.

RESULTS AND DISCUSSION

Our results are structured chronologically, following the development of the industry and the dynamics of the technology frames in it. Each section below summarizes our empirical findings on specific phases of this story, then discusses them in the light of theory.

Phase 1: the emergence of a technology frame

3D printing emerged through parallel developments in the 1980s in the US and Europe.\(^1\) 3D Systems (US, 1986) developed Stereolithography (SLA), a process of light-curing layers of liquid photopolymers. Stratasys (US, 1989) developed Fused Deposition Modeling (FDM), a process of extruding molten thermoplastic in layers. EOS (Germany, 1989) developed Selective Laser Sintering (SLS) and Direct Metal Laser Sintering (DMLS): processes of sintering layers of polymer and metal powders, respectively. Besides these three, several other firms emerged with similar processes. One is of particular interest: University of Texas spinoff DTM also developed SLS systems (with the first machines sold in 1994), but with little commercial success. However, this technology line became an important asset of 3D Systems when it acquired DTM in 2001.

\(^1\) The 1980s also saw developments in Stereolithography in Japan. However, this industry has mostly disappeared over time. See Wohlers (2015) for an overview of early developments.
Early generations of 3D printers found their first applications in rapid prototyping. For aerospace, automotive, and engineering firms, 3D printing was a way to bypass the laborious and time-consuming task of prototyping by hand. Stratasys’ 1996 annual report, for example, describes the application of its products as follows: “Rapid prototyping systems enable engineers and designers to produce models of their engineering designs faster and cheaper than with conventional manual methods” (Stratasys, 1997, p. 5). The main difference between the firms was the operating principle of the machines they built. Stratasys, for example, considered that it had a competitive advantage over the others, as its FDM technology was the only one not to use lasers, allowing it to be used in an office environment (Stratasys, 1997).

In these early years, OEMs’ main task was to find suitable materials and optimize the operating principle of the 3D printing machine (Beaman, Barlow, Bourell, Crawford, Marcus, & McAlea, 1997), as well as to develop an interface with digital inputs (Jamieson & Hacker, 1995). Once these elements were fixed, the machines developed only incrementally, to increase throughput and reliability and reduce costs. The business model settled on a “razor blade” approach, where consumables were the main source of profit.

The industry thrived from the start. All three OEMs started selling machines within two years of their founding and the industry grew to USD600M by 2000. Each company employed its own technology, but all shared a similar view of what the technology was useful for (prototyping and other product-development aids) and how the industry would develop (incremental developments for faster, cheaper, and more reliable machines). In other words, there was a consensus in the industry that the same pattern would continue into the foreseeable future (Wohlers, 1995; Kochan, 1997; Hull et al., 1995).

As the 3D printing industry came to be understood as the “rapid prototyping business,” the rapid-prototyping technology frame became established through a set of coherent choices. For
example, on the technology side, in 1996 3D Systems complemented its laser-based Stereolithography line with an extrusion-based ThermoJet line, more suitable for use in small office environments. On the product-design side, the OEMs improved their core products and expanded their offerings with peripherals and services to enhance the prototyping process. On the business-model side, distribution networks were set up to drive printer sales. These different elements reinforced each other and industry actors’ overall perception of the industry’s development, and engendered the industry-shared prototyping technology frame.

The prototyping technology frame guided firm action on all three levels, and these different domains of firm choices reinforced each other and the overarching technology frame. However, the predominant element of the technology frame, during this period, consisted of product choices. OEMs’ technological processes were different, but ultimately carried out the same task at comparable levels of performance. Business models were stable too. The most important choices facing firms related to getting the product design right in areas such as parameter selection, interfaces, and controls. The choices made in this period would shape the design of 3D printers for most of the course of the industry.

**Discussion 1: the interacting elements of a technology frame**

These developments resonate with the notion of technology frames as described in the literature (Orlikowski & Gash, 1994; Garud & Rappa, 1994; Kaplan & Tripsas, 2008). The technology frame captures the nature of the technology, its application possibilities, and what makes it valuable. In the broadest sense, then, it encapsulates what business a firm is in (Spender, 1989; Porac et al., 1989) and what it must do to succeed. We also know that firms have freedom to set industry rules (Santos & Eisenhardt, 2009) and that this freedom exists at the different levels of technology, product, and business model (Murray & Tripsas, 2004).
However, empirical work on technology frames has mostly covered their formation and consequences related to individual components only. For example, Garud & Rappa (1994) describe conflicting beliefs surrounding the best underlying technology for a given product. These beliefs concerned, among other factors, the evaluation and perceived success factors of the technology, and shaped the development pattern and the prevailing technological alternative.

On the product level, research related to technology frames can be mostly traced back to the interaction between product-development and customer choices as industries develop (Clark, 1985). For example, Grodal et al. (2015) describe the coevolution of technological designs and categories, showing that the definition of what a product should consist of, and what form it takes, is a result of the sociocognitive convergence process involving both producer and customer. Focusing on the customer side, previous work has showed how ambiguous new products become understood and defined over time through a process of categorization or labeling (Rosa et al., 1999; Anthony et al., 2016). On the producer side, research shows that product-design choices are guided by the producer’s technology frame. For example, Leonardi (2011) shows how different organizational units within firms have different “technology concepts”: ideas about what features an artifact should contain. On the aggregated firm level, Benner & Tripsas (2012) show that entrants tend to apply technology frames dictated by previous industry affiliation to product design in the new industry.

Finally, work on choices in business models around new technologies can be traced back to Teece (1986). He describes the important decisions firms must make to actually benefit from their innovations. These decisions, also described as “business models” (e.g. Amit & Zott, 2001; Teece, 2010), work on “management’s hypothesis of what customers want, how they want it, and how the enterprise can organize to best meet those needs, get paid for doing so, and make a profit” (Teece, 2010, p. 172). Additionally, such choices have been described in terms of the
demarcation of markets and the boundaries of the firm (Baldwin, 2008; Santos & Eisenhardt, 2009), as well as positioning in the industry architecture (Jacobides, Augier, & Knudsen, 2006). One example of how a technology frame shaped such choices can be found in Tripsas & Gavetti’s (2000) study, where Polaroid anticipated that it could impose its existing business model on a new environment, only to discover that this was not tenable. Another example is in Adner’s (2012) account of Sony and Amazon, which both tried to disrupt the traditional (book) printing industry through the introduction of e-readers. With the same technology, these firms envisioned and established completely different ecosystem surrounding their focal offering.

In summary, previous research has made headway in understanding how technology frames, as cognitive representations of the nature, usability, and value of technology, interact with choices firms make in several dimensions. Our results show that these dimensions are interrelated and together interact with the firm’s technology frame. Overall, firms’ choices in these three dimensions shaped how 3D printing became a prototyping technology.

**Phase 2: emerging challenges to the prototyping frame**

In 2000, airplane manufacturer Boeing used 3D printing on a systematic basis for the first time to produce end-use parts. It already had extensive experience with 3D printing as a prototyping technology. In 1999, the avionics system of its FN18 fighter jet program underwent a complete redesign. Avionics require highly specialized and complex air-duct systems to meet strict requirements. The redesign provided an opportunity to incorporate 3D printed parts, and Boeing successfully manufactured the air ducts using laser sintering (with DTM machines).

This use case demonstrated the applicability of 3D printing for manufacturing to the wider aerospace industry, and other manufacturing industries too—and the value it potentially offered. As a manager involved in the program at Boeing at that time told us:
First of all, it’s Boeing. So it’s a huge company known worldwide. Secondly, it’s parts that are flying on an aircraft, every single day. [...] So I think that it proved to the world, and certainly to the aerospace community, that these technologies aren’t just restricted to doing concept models and functional prototypes with a limited lifespan. [...] It really showed the world, “Boy, if you can put these parts onto airplanes, why can’t you do it for other products?”

From 2000 on, manufacturing industries started picking up on the opportunity, largely prompted by customers. As EOS’ CEO recalled, “These companies saw the potential for additive manufacturing as a serious production tool. And once they had seen it, they wanted it” (interview in TCT magazine, 2014). Direct manufacturing applications grew from less than 5% of total 3D printing industry revenue in 2003 to 43% by 2014 (Wohlers, 2015). Trade journal articles and books started appearing, describing opportunities, considerations, constraints, and costs of direct manufacturing (e.g. Hopkinson & Dickens, 2001; Hague, Campbell, & Dickens, 2003; Gibson et al., 2006; Hopkinson et al., 2006).

The 3D printing OEMs, by then firmly ensconced as industry leaders, recognized they possessed a potentially revolutionary technology. From 2000, they started advertising themselves, their products, and 3D printing technology in general increasingly as enablers of direct manufacturing, as well as (or instead of) prototyping. Furthermore, they established new, individually branded programs for direct-manufacturing applications (Advanced Digital Manufacturing for 3D Systems, 2002; Direct Digital Manufacturing for Stratasys, 2007; e-Manufacturing for EOS, 2002).

The OEMs also adapted their technology, products, and business models. As technological developments unfolded, they learned that some of the available processes were more suited for direct manufacturing than others. Of the polymer systems, SLS and (to a lesser
extent) FDM turned out to be suitable, along with metal systems in general. Accordingly, OEMs expanded their technology portfolio to include technologies and materials suited for manufacturing applications. In 2001, 3D Systems acquired DTM, the SLS firm whose machines were used for the Boeing air ducts. It further developed polymer-coated steel powders to use with these machines. In 2008, it gained access to DMLS technologies. Stratasys developed its FDM systems into direct-manufacturing systems, and briefly resold metal printers (from a small Swedish OEM) in 2006. In 2014, it started servicing parts using SLS and DMLS printers. EOS kept improving the sintering technology lines it already had.

Additionally, OEMs started to expand their offerings, from machines to platforms and complete solutions. They improved software and design-aid products along with their machines, introduced more ancillary products surrounding the printing process (e.g. for post-processing), and started offering consulting services. 3D Systems and Stratasys additionally set up service bureaus to offer parts services, to compete with an emergent downstream industry of intermediaries (3D Systems in 2009, Stratasys in 2005).

The OEMs had similar customers and mostly operated in the same markets. Additionally, they all had access to the same technological field, albeit from different starting points (e.g. different materials). They seemed to be moving in the same direction—to market 3D printing for direct manufacturing and become solutions providers to facilitate adoption. All were still very successful: between 2000 and 2014, 3D Systems achieved a CAGR of 13.63%, Stratasys 24.32%, and EOS 16.1% (revenue data from firm documentation).

Nevertheless, OEMs’ attempts to disrupt the manufacturing industry fell short. As Hopkinson et al. (2006) describe it: “The problem at this point is that Rapid Manufacture is seen as merely an extension of Rapid Prototyping and so parts are not seen to be suitable or intended
for end use. This ‘baggage’ of Rapid Prototyping is probably a larger hurdle to the uptake of Rapid Manufacturing than any of the technical issues that we face” (p. 3).

The most important implication of direct manufacturing as a 3D printing application was that it entailed a new set of requirements on machines, incompatible with the prevalent prototyping-technology frame. This difference of application fundamentally affected all aspects of the 3D printing frame. For example, the technological process as a whole was exposed to different “evaluation routines” (Garud & Rappa, 1994). As a manager in a large automotive customer explained:

You know, I wouldn’t build a structural part unless it’s well tested. Using the metal process, or plastics process. Until I’m absolutely a hundred percent confident that it’s going to do what it needs to do. And react the same way as the current product.

These expectations also fed into product design choices. As an EOS manager explained:

If you are just for Rapid Prototyping then you have no need to define a system that you can scale. [...] The number of complexities is very low. But here we are entering into companies that normally use five-axis milling devices, they expect mature products.

For all the new labels and brands promoted by the OEMs, the direction of development in the 3D printing industry at the time was still governed by the dominant technology frame (prototyping). That is, OEMs were focused on making their machines faster, cheaper, and more office-friendly, as they perceived these dimensions to be the competitive grounds. A fundamental change of technological frame was required. Whereas the convergence on an industry-wide frame fostered adoption and development in the early years, now it was becoming a straitjacket.

From 2000 on, the main difference among the OEMs was the extent to which they actually transformed their technology frame. 3D Systems and Stratasys hardly did so at all; they tried to enter the direct manufacturing market with their rapid prototyping frame. EOS, however,
managed to become more geared towards direct manufacturing applications. Below we outline the process of frame evolution for the three OEMs.

**3D Systems and Stratasys: attempts to enter manufacturing with a prototyping frame**

In the technology domain, 3D Systems and Stratasys both expanded into more advanced technologies, mainly through private-label agreements and acquisitions. However, these moves did little for the development of internal capabilities surrounding these new technologies. 3D Systems, for example, did not seem to realize that its acquired technology line was fundamentally different from its own, and treated metal printing technologies as merely a stronger variant of polymer printing. As a former employee explains:

> At first they did not realize that [it was so different]. [...] They thought, “Well, we make polymer parts here and there, but if you really need something stronger, we’ll print it in metal.” Even though this is the wrong approach.

Stratasys, similarly, did not develop capabilities in developing SLS or metal printers itself at all, even as it gained access to the technology lines. It offered these technologies to customers only through its service arm, using competitors’ machines.

In the product domain, similarly, little changed for these OEMs. They remained within their technological trajectory, and core designs stayed the same. As a former Stratasys manager told us:

> As we look into the future, the mean time to failure on a production machine and the types of controls and the amount of codes that run that machine, throughput, yield, cycle time, these are words and metrics that are foreign to 3D [Systems] and Stratasys’ worlds. And hence their emphasis will stay on the prototyping world, picking up a little bit of nichey manufacturing here or there.
Openness of technical architecture was one aspect of 3D printer design that became crucial for direct manufacturing. For prototyping applications, machines could be completely closed, essentially functioning as a black box. In fact, such a design was actually preferable for the OEMs, as it bolstered the dominant “razor blade” business model, allowed for the protection of proprietary software and materials, and reduced complexities on the production side. However, for direct manufacturing, open architecture was crucial, for customers to be able to certify produced parts, and to leverage intellectual property in their products.

For 3D Systems’ SLS machines, development actually moved away from open architecture. Around 2000, a sintering polymer was discovered, pretty much by chance, that far outperformed existing polymers. This led to machines being optimized around the new material, which limited the control possibilities of the user.

Finally, in terms of business models, 3D Systems and Stratasys again went for options guided by their existing technology frame. Both firms became complete solution providers over time, to lower barriers to adoption. This worked to an extent, allowing firms to execute one-time projects without having to invest much in new systems and knowledge. However, to reorganize existing routines and organizational structures around a new manufacturing technology, customers needed to gain control over the 3D printing process. 3D Systems and Stratasys, however, used their platforms to reinforce their position as a bottleneck in the industry—for example, by locking customers in with materials and systems.

**EOS: moving toward a new frame**

In 2000, EOS was in a similar position to 3D Systems and Stratasys, but differed in terms of its technology base. It already owned polymer and metal technology lines, which together were
capable of spanning the range of applications from prototyping to manufacturing, and it continued to develop these technology lines with a heavy focus on engineering capabilities.

In terms of product design, EOS respected customers’ wish for more control. However, it faced a tradeoff. With only limited knowledge yet available in the industry, versatility in process parameters came at the expense of reliability and repeatability in the process and part quality itself. On the metals side in particular, 2000s technology was not yet very reliable. Users often overestimated the technological capabilities of metal 3D printers, leading to conflicts with printer suppliers in cases of part failure. The easiest solution for EOS was to restrict control over parameters—but that led to conflicts with more sophisticated users.

Eventually, in 2009, EOS found a middle ground through its Part Property Management (PPM) solution. Customers could, as an additional service, ask EOS to adjust parameters for them and re-certify these new settings for new applications. This program was further extended in 2012 to allow customers to include more intellectual property in these settings.

Things changed on a more fundamental level for EOS too. Even though it was already at the forefront of technological developments, it realized that incremental improvements along the current trajectory would not be enough to make the leap to direct manufacturing. It decided on a root-and-branch redesign of its organization, from the product design domain right up to firm strategy. In other words, it broke with its existing frame to establish a new one. As a senior manager told us:

[In 2006, General Electric] asked us, and [EOS founder/CEO] Dr. Langer too, to put much more emphasis on skipping from pure rapid prototyping to manufacturing. And so he changed his entire management team. I think it started in 2010 or so. [...] Dr. Langer switched the strategy of the company from system producer and somebody who sells machines, to a solution provider. And here he was bringing in new management
with a lot of expertise in much larger businesses. And then we also came up with new solutions, from hardware to software to services especially. And this is something that was also a transformation of EOS at that time.

This new direction fed back all the way into product design:

So this means that purely for conformity reasons, I think the new management had a much better understanding of the demands and requirements of the future production customers. And therefore I think we see everywhere how they also impact the business and the way we are setting up our business. Especially the technology side, too. So our systems are more scalable, they are more connected, they have a more modularized approach than in the past.

**Frame rigidity and drivers of change**

The most important factor that sustained the existing technology frame was that the OEMs were never under pressure to change it. They quickly rose to dominate the industry and had hardly been threatened. With a business model that was generating steady profits, exponential industry growth, and no rivals in the market for direct manufacturing, speed of adoption was not much of an issue. In other words, the existing situation reinforced the validity of the technology frame.

Additionally, polymer systems especially were confined to a limited set of materials, creating a monopoly situation for the OEMs. Finally, the new application opportunity originated from relative outsiders. It was not (yet) a part of the OEMs’ collective technology frame, and was thus filtered out of their decision-making process. As a former Stratasys manager explains:

Most of these companies grew up in the prototyping world and had a prototyping mindset, not a manufacturing mindset. So it was very hard to get any of them in the early 2000s to start thinking about having multiple machines sitting in a manufacturing
environment that was going to be running lots of material, and running around the clock with whatever additive process. They weren’t thinking that way; they thought that was still 20 years off.

In this respect it is telling how EOS did manage to overcome this cognitive barrier: General Electric, the most innovative user of 3D printing, directly asked and convinced their CEO to break their frame. 3D Systems and Stratasys seemed less receptive to customer requests.

In summary, the development of the main 3D printing OEMs’ offerings can be described as follows: All three firms moved from being standalone machine providers to complete solution providers, to support the uptake of 3D printing for manufacturing applications. However, 3D Systems and Stratasys did so guided by the prototyping technology frame, which dictated that control over the technology remained with the OEM. Over time, EOS moved out of this frame to some extent, also offering complete solutions but positioning itself more as a technology partner, aiding customers in reforming their manufacturing process around 3D printing. Asked whether 3D Systems and Stratasys could easily make the jump to get a foothold in direct manufacturing, the former manager of Stratasys comments:

*It’d be difficult. It’s going to be so difficult. Again, you have to realize that the leadership culture inside the company and the people inside the company—once you have a prototyping mindset, it’s very difficult to change that mindset.*

Incidentally, both 3D Systems and Stratasys have appointed new CEOs over the course of 2016, before launching new campaigns and programs aimed at bridging the gap between prototyping and manufacturing applications.

Although the OEMs had always had relative freedom in maneuvering between technological bases (as shown by their many acquisitions and private-label agreements), their starting point in 2000 was pivotal to the flexibility of their frame. Of the technological
alternatives available, EOS’ were more suitable for direct manufacturing, giving them an advantage in understanding and adapting to direct-manufacturing requirements. Conversely, 3D Systems and Stratasys encountered adjustment problems, having to match existing prototyping-focused knowledge and operations to new technologies and new requirements. Thus, in this period, technology choices were the driving element of the technology frame.

**Discussion 2: the dynamics of technology frames**

Our findings on the OEMs’ struggle to take their game-changing technology out of the prototyping studio and on to the factory floor has clear ties to an important duality of technology frames. On the one hand, frames are a means for convergence: as actors with conflicting technology frames interact, they converge on a single frame that coordinates and guides further developments (Orlikowski & Gash, 1994; Garud & Rappa, 1994; Kaplan & Tripsas, 2008). On the other hand, misalignment between frames can be a source of dissonance and lead to change, especially as a result of environmental change (Kaplan, 2008).

The converging mechanism of technology frames clearly leads to the canonical prediction that incumbents stay within established trajectories and are less likely to introduce disruptions. Discontinuities must then come from industry outsiders, or gain momentum after fundamental problems or limitations emerge within the current frame (Kaplan & Tripsas, 2008).

However, this set of predictions about the emergence of discontinuities is troublesome for the explanation of disruptive innovation from the disruptor’s (or outsider’s) perspective. After all, to be successful, disruptors need to both fit with existing industrial structures and routines and diverge from them. They must devise a technological form and applications that radically deviate from established practices in the industry they are to disrupt. At the same time, however, they
must be able to convince customers with pre-existing expectations of their product, and fit with the currently dominant frame of critical industrial actors (Adner, 2012).

This process entails a number of challenges, including how to “co-opete” with existing actors (Ansari et al., 2016). Moreover, disruptive innovations often have to develop in market niches, as they are initially unable to challenge incumbents. If the initial embodiment of a technology differs considerably from that needed for disruptive purposes, firms also face the challenge of having to adapt their technology frame during the development of the industry.

Our findings show the dual role of technology frames in the development of the 3D printing industry. The initial application for the technology was found in prototyping. Its use in this domain offered clear advantages for manufacturing industries and dovetailed with their needs, improving their product-development process with few drawbacks or adjustment requirements. In other words, it was not at all disruptive. In this domain, and other related non-disruptive applications (see Sandström, 2016), 3D printing has enjoyed rapid uptake. The OEMs did not see direct manufacturing as a possible application until it was presented to them by a lead user (Von Hippel, 1986). Boeing’s use case provided a highly visible example (Freeman & Louçã, 2001) that direct manufacturing was in fact a feasible and commercially attractive application—but it didn’t fit with the prevailing technology frame.

While the process of convergence around a technology frame worked well in the prototyping era, it now exerted resistance on technology suppliers. Additionally, there were still few forces to stimulate change on the OEMs’ side. As a clear technology frame of 3D printing as a manufacturing technology did not exist (yet), there was no clear alternative path for OEMs to take. The dilemma of EOS in its search for the optimal product openness illustrates this. Also, the OEMs were still hardly challenged in the competitive arena.

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As discussed, of our three OEMs, it was EOS that most clearly saw the need to fundamentally transform its technology frame. This has led to a process of slowing down as a firm (Kaplan, 2008), as EOS decided to mostly step away from the by-then-mature but still growing prototyping market, with sales and size trailing behind the two American OEMs.

**Phase 3: Increased competition, different frames**

Recently, the 3D printing industry has experienced entry from seemingly unrelated industries. The first wave broke in the mid-to-late 2000s, with new European metal printing firms following in EOS’ footsteps with very similar technology and product designs—but varying in terms of which niches they targeted and their choices in terms of openness.

However, after 2010, new entrants emerged from multiple directions. They included new entrants seeing an unmet market need, both in metals and in plastics, but also industry complementors stepping into 3D printing (e.g. CAD solutions) and diversifying firms from related industries, (e.g. machine tools and robotics, but also 2D printing through HP).

Additionally, 3D printing customers are increasingly taking it upon themselves to step into machine manufacturing, either working together with OEMs or acquiring them.

These new entrants use a range of technologies—some established, some new. What they have in common is that they espouse a very different technology frame from the original 3D printing firms, mostly in terms of the openness of their machines. Commenting on the mismatch between customers’ needs in 3D printing for manufacturing and OEMs’ receptiveness to these needs, one customer described recent developments as follows:

We clearly see that there are two or three types of OEMs. One type of OEM does not believe in this story and wants to stick to their given, established, and also successful-up-to-now strategy, which is okay. We see a second type of kind of gray-ish OEM that
is slowly opening up and buying into this idea, and the third type is a very open kind of OEM [...] And especially the third wave is mainly coming from a machine-tool environment or a production-machine environment, so they are actually used to this open and cooperative approach with end-customers.

EOS, having moved to the manufacturing front most effectively, now finds itself in a new competitive arena with these new entrants; this competition is mainly between technology and customer bases. EOS has a background in the technology, but has to find access to customers. Competitors from, for example, the machine tool space have the knowledge of customers, but still lack the technological skills and experience needed to create robust 3D printing solutions. As a senior EOS manager told us:

So if somebody comes from that [machine tools] and understands customer demand much better, and has a base just with field service engineers, with technicians, or even with an academy, then of course you can utilize this much better. [...] Our challenge is to step in that direction too. Their challenge is to step into the technology.

One such new entrant saw an opportunity in the fact that technology was ready but the products on the market were not bridging the technological potential to customers’ wishes. Unhindered by the existing technology frame, it could enter the market with a different frame much closer to customer needs. As the CEO explained: “I think what we do really differently from others is that we really start from the customer perspective.” This different frame manifests in the design principles and even the perceived role of the firm in 3D printing applications. From this perspective, a 3D printer is a versatile production tool, adaptable to the user’s needs, rather than a “black box” controlled by the supplier. As the CEO explained:

Ultimately it's their machine, they have to make the best products with it. We will help them do so and we also enable them to, for example, freeze those settings if they want
to, for example because they have certified a product. [...] But we believe in full openness, also in terms of hardware. [...] So that they can also add process steps to the machine that are specific to the application that they have in mind.

A second example of a new entrant is HP, diversifying from its inkjet printing business. It plans to sell its first-generation machines in 2017, although its announcements so far shed light on the choices it has made in bringing 3D printing to market.

HP developed its own polymer-based technology. In its products, HP focuses on quality control as an integral part of its machine development. In its business model, it has chosen a very open platform approach, similar to other new entrants but diverging from the (polymer) OEMs and, remarkably, its own inkjet printer business. Its 3D printing solution allows for externally developed materials, and also third-party software and applications (3D Printing Industry, 2016).

Altogether, in this period, business-model choices (mostly about openness and platform-based approaches) form the most important domain of choices in the 3D printing technology.

**Summary: temporal dynamics of technology frames**

3D printing as a technology has been widely heralded for its potential to revolutionize manufacturing. We observe that this potential is yet to be fulfilled. The firms that pioneered 3D printing technologies have tried to bring their products to the direct manufacturing market, but relying on technology frames formed at a time when prototyping was their favored application area. This accounts for the persistently non-disruptive impact of additive manufacturing. While the strategic intent was clear (use 3D printing to enter direct manufacturing), the frames firms deployed to make their concrete choices were still the old ones. The interplay of technological, product, and business-model choices made the adaptation process slow and cumbersome. Yet, we
also observe an increasing heterogeneity, putting distance between Stratasys and 3D systems on one side and EOS on the other.

Figure 2 illustrates the development of technology frames over time. It shows how, before 2000, an initial technology frame existed that was highly compatible with prototyping applications. When direct manufacturing emerged as a viable business segment in 2000 (in response to Boeing’s initiative), the OEMs began to diverge.

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Insert Figure 2 about here
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GENERAL DISCUSSION

3D printing has been heralded as the cornerstone of a new industrial revolution. Yet, its potential appears to be still far from being achieved. We have argued that while technologies per se matter, their impact also depends on other factors, captured by the concept of technology frame, which we used to interpret the complex interplay between technological, product and business model choices. The technology frames of the OEMs have heavily affected how they shaped 3D printers and the business solutions they enable, and subsequently the degree of disruptiveness the technology could attain.

**Technology frames hindering distant applications over proximate ones**

We observed the difficulties facing the OEMs to realign their technology frame to customer requirements that emerged clearly in the early 2000s. Disruptive innovations, whether they are products or processes, usually have to cross boundaries across applications and market segments on their way to mainstream markets (Christensen, 1997). If a firm’s technology frame is still fluid in the early stage of a new technological development (Kaplan & Tripsas, 2008), every step
towards a concrete application of the technology is an added nudge on firms to settle into a
frame. Existing applications and market positioning choices set evaluation routines which further
reinforce firms’ initial choices (Garud & Rappa, 1994).

**Technology frames make it difficult to give up control over innovation**

Our findings show that the locus of control over 3D printing technology (resting with either the
OEMs or the customer) is still an open issue underpinning the ongoing discussion about 3D
printing and its ‘disruptive’ impact on manufacturing. The OEMs that developed the technology
were hesitant to give up control over it.

The tradeoff faced by the OEMs is clear. If a pioneer allows the downstream ecosystem to
adapt and reshape the innovation, this fosters adoption of, and realignment around, the
innovation, but at the risk of endangering its position as an industry bottleneck (Teece, 1986;
Jacobides et al., 2006). If, instead, it keeps strict control (e.g. by restricting access to intellectual
property or adaptation of the innovation), it can capture more value from it, and steer the role of
the technology (and itself) in the downstream ecosystem. However, this may limit adoption to
such an extent that the innovation never reaches a critical mass (Rogers, 2010). This ‘control
trap’ seems most dangerous for disruptors in complex ecosystems, where many actors’ incentives
need to be aligned for technologies to gain traction (Adner, 2012).

Another fundamental property of technology frames might deter firms from giving away
control of their innovations. Ultimately, products are made following rules and assumptions that
the supplying firm holds about the technology and the product around it. These rules and
assumptions do not necessarily match those of the users, especially in early stages of an industry,
as frames have not yet converged (Kaplan & Tripsas, 2008). This effect naturally constrains the
freedom users have in adapting the technology to their wishes or expectations.
Our would-be disruptors have provided some valuable lessons for managers: restricting access of technologies and products to customers is a double-edged sword. However, examples of particularly EOS show that there are many intermediate solutions to be found, for example in selling openness as part of a business model.

**The (cognitive) second mover advantage**

In our observations, the OEMs that started the 3D printing industry have been in a position of technological leadership for the entire development of the industry. Yet, it is these OEMs that are holding back the disruptive potential of the technology. Now, technology barriers are falling and new entrants move in with different technology frames. The needs and preferences of users are clear. All OEMs have stated they want to enter direct manufacturing. Yet, at the time of writing, the new entrants seem to be best positioned for exploiting the most profitable application of the technology, thereby condemning the former technology leaders to niches.

These findings shed new light on the second mover advantage often seen in new industries (Hoppe, 2000, Kretschmer, 2008; Christensen, Suarez, & Utterback, 1998). This advantage is often explained in technological terms, where followers have the advantage that they enter the industry after some ambiguity surrounding the technology has dissolved, and signs of a dominant design have started to appear (Abernathy & Utterback, 1978; Suarez & Utterback, 1995; Christensen et al., 1998). An alternative explanation emerging from our study is that fast followers can also learn from mistakes in the technology frames of industry pioneers. More precisely, the problem here is not the technology per se, but rather the (in)ability of pioneers to reorganize the complex interplay between technological, product and business model choices that constitute their technology frame.
CONTRIBUTIONS

Our main contribution to the literature on disruptive innovation follows from the cognitive lens we apply to understand firm dynamics surrounding their technologies. We explain firm choices on different dimensions as part of technology frames, broad assumptions and perceptions about technology, applications and value. By using these technology frames as the interface between technological possibilities and application domains, and by focusing on an entire industry rather than a single firm, we can explain why different firms turn the same, potentially disruptive technology into solutions with varying pervasiveness in downstream industries. Thus, we shed light not only on the matter of whether a new technology becomes disruptive, but also by which firms and why.

A second contribution to the literature on disruption follows from our research design of following suppliers and users of a potential disruption in parallel. Our findings highlight the necessity of downstream reorganization around a new technology as a key challenge for disruptors. This downstream reorganization poses dilemmas for disruptors, for example in finding the optimal locus of control over the innovation and the role of the firm in the innovation ecosystem (Adner & Kapoor, 2010; Adner, 2012). The responses of disruptors to these conundrums are critical for the making of disruption.

Our study also provides valuable contributions to the literature on technology frames. Previous empirical work on technology frames focused on either the side of production (e.g. Garud & Rappa, 1994; Benner & Tripsas, 2012; Leonardi, 2011) or on technology adoption (Orlikowski & Gash, 1994; Rosa et al., 1999). Following our holistic research design and the inclusion of multiple data sources over a long period of time our study departs from technology suppliers but also emphasizes the interactive between dynamics on both sides of the industry in explaining firm choices.
LIMITATIONS AND SUGGESTIONS FOR FUTURE RESEARCH

Future work on disruption can build on some of the limitations we encounter in this study. Our first limitation lies in the tradeoffs we had to make in the research design. While we believe our design was useful to uncover drivers of firm heterogeneity and disruption in the context of a new technology in general, we lacked an in-depth view on decision-making and dynamics of technology frames within the firms. This in-depth view has been the virtue of many studies on cognitive frames (e.g. Orlikowski & Gash, 1994; Kaplan, 2008). We think in-depth, longitudinal research on how innovating firms recognize the disruptive potential of their technology and translate this into (re)evaluations of their strategic choices would be a valuable direction.

Second, while we conceptualize technology frames as overarching filters and guides to action, we observe that at different times, different elements of the frame have been more prevalent (in our study moving from product design choices to technology and finally business model choices). Unfortunately, our access and level of detail in data did not allow us to systematically research this particular dynamic. However, we do believe this shift of importance over different domains of development is important, also in relation to the development of the industry lifecycle (e.g. Utterback & Suarez, 1993; Utterback, 1994) and thus invite future work to focus more on this aspect.

Finally, our potential disruption of study was a process innovation, rather than more widely studied product innovations. While we believe process innovations to be particularly relevant for questions of disruption in downstream industries as general-purpose technologies (Bresnahan & Trajtenberg, 1995), we recognize limitations in generalizing to product innovations. Future work on different types of disruption could take this inherent difference into account.
REFERENCES


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Notes: Some interview partners had different roles over time. For 3D Systems and Stratasys, our interview partners are former employees.
FIGURE 1: A MODEL OF DISRUPTORS’ CHOICES AS ELEMENTS OF A TECHNOLOGY FRAME

Product-design choices

Technology Frame

Technology choices

Business-model choices
FIGURE 2. DEVELOPMENT OF THE 3D PRINTING INDUSTRY