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Breadth-of-impact frontier: How firm-level decisions and selection environment dynamics generate boundary-spanning inventions

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ABSTRACT

In this paper, we provide an ex-ante explanation for why some technologies such as James Watt's steam engine move successfully across broad technological fields, while other technologies do not. Using a sample of VC-backed biotechnology firms, we examine firm knowledge exploration choices along three dimensions—the decision to build from technologies across broad fields, the decision to explore application domains that are new to the firm, and the decision to mix these two options at the same time. We argue that firm-level invention decisions find differing responses when received by the selection environment. We find evidence of a "breadth-of-impact frontier" for technologies, wherein the choice of whether a firm should enter into a new application domain than those of the past should be informed by the degree to which the technology is citing prior work narrowly or broadly. The findings suggest that the belief that broad sourcing diversity will always result in greater citation diversity requires some caveats. The results contribute to the understanding of not only how entrepreneurial firms evolve but also how individual firms contribute to collective progress.

1. Introduction

For some reason, some technologies such as James Watt's steam engine move successfully across broad technological fields, while other technologies do not. In the case of Watt's engine, the technology moved into fields as widely divergent as water pumping in the coal mining industry to propelling locomotives in the railroad industry (Diamond, 1999). As Levinthal (1998) describes, the porting of existing technology to a new domain of application triggers the transformation of technology across domains. In the case of these boundary-spanning technologies, insights and discoveries from different organizations (or organizational units) are merged into new products or new technical solutions (Rosenkopf and Nerkar, 2001).

It should be no surprise then that scholars traditionally have attributed the emergence of such boundary-spanning technologies to particular abilities of the individual firm. A firm's so-called "second-order competence" (Rosenkopf and Nerkar, 2001) is the ability of the firm to create new knowledge through recombination of knowledge across boundaries. Alternatively, a firm's "architectural competence" (Henderson and Cockburn, 1994) represents the multidimensional ability to access new knowledge outside the boundaries of the organization and to integrate knowledge flexibly across disciplinary class boundaries within the organization. Both firm-level abilities may play an important role in creating technologies with powerful breadth-of-impact (i.e., the generality in utilization of an invention) in the economy (Hall et al., 2001). In such cases of second-order or architectural competence, entrepreneurial firms can impact technological progress in an individual way, where discoveries are made by the entrepreneurial firm and these discoveries and their benefits are internalized (Fairtlough, 2000). What these traditional views tend to set aside, however, is the role of the ability of others—not just the focal individual inventing firm—to act in the technological community, i.e., the selection environment (Levinthal, 1998). Discoveries are picked up, utilized, and improved upon by other firms in the technological community, so that in addition to impacting technological progress in an individual way, entrepreneurial firms also impact technological progress in a *collective* way. Thus, boundary spanning technologies evolve over time through the actions within the selection environment.

In this paper, we attempt to shed light on the interplay between individual and collective aspects of invention by investigating the choices made by the individual inventing firm and the choices available to other firms in the selection environment as a result. We contribute to the literature in three ways. First, we contribute to the understanding of not only how entrepreneurial firms evolve but also how individual firms contribute to collective progress. Firms have choices that can impact not just the individualized invention process (e.g., Freel,

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2005), but the cumulative invention process that occurs outside the firm as well (Holmen et al., 2007). We build to the logic that firm-level decisions can either limit or enhance whether others are able to build on a given invention, which feeds into how much breadth-of-impact a given technology can muster. Using a sample of VC-backed biotechnology firms, we examine firm knowledge exploration choices along three dimensions—the decision to build from technologies across broad fields, the decision to explore application domains that are new to the firm, and the decision to mix these two options at the same time. Second, we contribute that knowledge exploration choices at the inventing firm level mix with aspects of the selection environment to yield differing degrees of breadth-of-impact for a given technology. The belief that broad sourcing diversity will always result in greater citation diversity requires some caveats.

The paper is structured as follows. First, we describe the prior work on selection environments for technologies and then describe what the process of entering a new application domain means for a technology in the selection environment. We follow with a discussion of how sourcing diverse pools of knowledge may draw broad attention to a technology, and then describe how these two main effects may interact. Thereafter, we present our methodology, our measures and our model specification. We review the findings of the empirical model, and then conclude with a discussion of the theoretical and practical implications of our findings. Specialization provides depth for the firm, but it may not lead to larger overall breadth-of-impact. At the same time, a willingness to step out of specialization may harm the ability of a firm to leverage past successes, but it may create an avenue by which others may build upon that knowledge. We find evidence of a breadth-of-impact frontier for technologies, wherein the choice of whether a firm should enter into a new application domain than those of the past should be informed by the degree to which the technology is citing prior work narrowly or broadly.

2. Theory and hypotheses

2.1. Technology selection environment

A necessary condition for the survival—let alone success—of an invention is that it be perceived as worthwhile by the organizations that directly determine whether it is used or not (Nelson and Winter, 1977). Accordingly, the technological community plays a key role in how a technology evolves (Nelson, 2000). The selection environment determines the relative use of different technologies over time and influences the path of productivity growth generated by any given invention. This is in addition to influencing strongly the kinds of R&D that firms and industry will find profitable to undertake (Nelson and Winter, 1977). The identification of opportunities by actors derives from changes in the system at the hands of other actors (Holmen et al., 2007). An initial invention may take into account the selection criteria of the technological community and the end user; thus an initial invention is the inventor's representation of the selection criteria. As Nelson (2000) states: "the argument is not that technologists can clearly see exactly the nature of the new departures that will solve a perceived problem, or make a desired improvement." As a result, multiple representations may be formed. The technological community eventually tends to converge on the best alternative (e.g., van der Valk et al., 2009), as there seems to be some ultimate technological criteria of merit, whether pre-existing (i.e., "natural") or developed through interactions (i.e., "emergent") (Nelson, 2000).

In recent years, selection environments have been conceptualized as feedback loops created by market selection processes, which simultaneously constrain and focus firm choices regarding what learning the firm should undertake and what complementary assets the firm should pursue. This research has expanded on the effects of selection environments on technological success/failure and paradigm shifts (Watson, 2004); on the self-organization of networks (Rycroft and Kash, 2004); and on the management of strategic niches (Tsoutsos and Stamboulis, 2005). In this paper, we expand on the concept of selection environments in order to better understand the nuances surrounding the impact of inventions on cumulative technological progress.

The union of organizational factors that create a "technological push" and environmental conditions that create a "market pull" underlies the notion of what Nelson and Winter (1977, 1982) and Dosi (1982) have termed technological trajectories. Firm-level technological trajectories represent the expansion of a core set of solutions favored by institutional forces that condition their selection and survival (Kim and Kogut, 1996). Thus, revealed firm-level trajectories become a conjunction of firm-level and industry-level factors. We know from prior work that the domain may play a role in developing the functionality of an existing technology after the technology is applied to a new domain (Levinthal, 1998). When this happens the domain changes the invention to meet different input availability and output selection criteria (Banerjee, 2008; Levinthal, 1998). Once a technology is developed further in a new application domain, it is ready to possibly enter an entirely new application domain, or even the original domain (Banerjee, 2008; Levinthal, 1998). In other words, after the entrepreneurial effort to make the move from one application domain to another is made, the selection environment continues in the technology's further application to other application areas. It also could be that technologies that are readily applied to a new domain are more able to be applied to new domains. As a consequence, it is a combination of firm choice and the selection environment that may influence the overall impact of a given technology.

2.2. Entering new application domains

After initial invention, entrepreneurial firms need to continue innovating. It is insufficient to rest on one's laurels with a single invention; a firm must consider ways to repeat the feat long into the future. Competing in rapidly evolving industries poses the complex problem of choosing what knowledge should be developed (Kim and Kogut, 1996). A firm may take existing technological knowledge and port it into a new technological space, generally referred to as an application domain. As an example, a firm may have built a specialty in cellular division which conventionally is used by the firm in looking at the growth of cancers. If that same firm were to ply that knowledge of cellular division in a new technology space, such as skin grafting, then the firm would be taking an existing knowledge base and exploiting it in a new application domain. The exploration of new application domains, therefore, represent attempts to gain economies of scope from existing knowledge bases.

One primary benefit of innovating in an existing application domain is the need for significantly less resources. Searching recently created knowledge conserves cognitive capabilities (Cyert and March, 1963) and reduces search costs (Katila, 2002). This may explain why many technology-oriented firms, such as biotechnology firms, tend to specialize in relatively few technological subfields (van der Valk et al., 2009). This also may explain why firms often attempt to generate new products by building on prior product successes through such tweaking as new configurations (Cheng and Shiu, 2008). Because incorporating knowledge of a new domain would alter a firm's existing technology, the