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TECHNOLOGY EMERGENCE THROUGH ENTREPRENEURSHIP ACROSS MULTIPLE INDUSTRIES

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Radical process discontinuities provide opportunities for the founding of new firms across multiple industries; however, little is known about such emergence activity. This article examines nascent technology emergence by studying patterns of related entrepreneurial activity across multiple industries based on a radical process discontinuity. Using historical and statistical methods to examine all nanotechnology firms founded before 2005, I find that during technology emergence, entrepreneurship occurs first in upstream industries. These upstream entrepreneurs provide the technological foundations that enable the founding of firms in other industries developing the technology. The results show the role of industry interaction in the development of both upstream and downstream industries. Implications for entrepreneurs and technology emergence are discussed. Copyright © 2010 Strategic Management Society.

INTRODUCTION

New technologies and technological change have long been maintained as fundamental drivers of economic growth and the formation of new industries and firms. Schumpeter (1942) argued that revolutionary technologies shape and reshape the economic landscape through *creative destruction*, a process by which new market opportunities are created while others are destroyed or replaced. Thus, the emergence of a new radical technology and the subsequent development of technological innovations provide opportunities for entrepreneurs to found new organizations and for incumbent firms to explore new markets (Aldrich and Ruef, 2006).

A wide range of studies have examined the dynamics surrounding radical technology emergence after a breakthrough or discontinuity. These studies focus on competitive advantage through complementary assets (e.g., Stieglitz and Heine, 2007; Rothaermel and Hill, 2005; Rothaermel, 2001; Tripsas, 1997), incumbents' performance (Rothaermel and Thursby, 2007; Jacobides, Knudsen, and Augier, 2006; Hill and Rothaermel, 2003; Arend, 1999), the displacement of incumbents (Tripsas, 1997; Mezias and Kuperman, 2000), innovation appropriation and commercialization (He, Lim, and Wong, 2006; Dahlander and Wallin, 2006), and the development of a dominant design (Funk, 2003; Anderson and Tushman, 1990). Although these studies have greatly improved our understanding of the effects of radical technological discontinuities, they tend to emphasize a single industry, incumbent firms, and product discontinuities. However, a technology is not always developed in one industry alone and fundamental discontinuities greatly influence the development of all populations within a technologically interdependent community (Tushman and Anderson, 1986). In particular, while product technologies are often

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developed within a specific industry or NAICS code, process technologies can be applied across multiple industries. For example, the ability to modify or engineer genetic material has revolutionized the farming, food manufacturing, biotechnology, and medical industries, to name a few of its applications. The more fundamental the breakthrough, the more likely that the technology has a wide range of applications across multiple industries. Therefore, to understand the emergence of a radical technology after a discontinuity, it is important to examine its emergence across multiple industries. One setting in which this is particularly salient is after a radical process discontinuity, an area which has been largely overlooked in empirical work. Thus, this study attempts to build on previous studies by addressing technology emergence after a radical process discontinuity.

Similarly, the majority of technological discontinuity studies examine incumbent firms despite Wade's (1996) findings that new entrants are more likely to introduce new technology than incumbent firms. As a result, little is known about the emergence of a technology via new entrants. Observing entrepreneurship after radical technological discontinuities offers a rich context to examine new venture creation in an emerging domain of activity. This study goes beyond previous research by examining technology emergence through entrepreneurship across all industries in which the new technology is used. Specifically, two research questions are addressed. First, in which industries does entrepreneurship occur earliest during technology emergence after a radical process discontinuity? Second, during technology emergence, how does entrepreneurship in one industry influence that in others?

In this study, I examine a radical process discontinuity—nanotechnology, the manipulation of matter at a size scale between one and 100 nanometers (National Science and Technology Council, 2000)—as it is commercialized in multiple industries. To examine technology emergence, it is necessary to capture the activity of firms using the technology during its earliest years. I use a unique and rich dataset of all firms founded to commercialize nanotechnology in the United States through 2005. Over the course of the last four decades, nanotechnology has emerged from science fiction to scientific reality. Recently, nanotechnology has been used to address questions in a wide range of applications—from drug delivery, medical devices, and materials science to electronic sensors. Although it is not an industry unto itself, nanotechnology crosses several industries and, thus, provides a natural experiment for examining the emergence of a nascent radical process technology across multiple industries.

The article proceeds by first building hypotheses from technology emergence and entrepreneurship studies and integrating work on community ecology. By applying the community ecology perspective to technological emergence, we can gain a deeper understanding of the dynamics of technology emergence through entrepreneurship, especially the interaction of industries. The hypotheses bridge these two literatures, specifically attending to technology emergence in different industries via new firms.

RADICAL TECHNOLOGICAL DISCONTINUITY AND ENTREPRENEURSHIP

Technological discontinuities are breakthroughs that dramatically advance industries' price versus performance frontiers (Anderson and Tushman, 1990). Radical discontinuities are 'revolutionary changes in technology' that are clear departures from existing practices (Dewar and Dutton, 1986: 1422). These changes alter the foundation of a market. In turn, radical technological discontinuities create opportunities for entrepreneurship and foster the creation of industries (Schumpeter, 1942; Aldrich and Fiol, 1994; Aldrich and Ruef, 2006).

Radical technological discontinuities affect the market through product and process innovations. In contrast to product innovations—or the commercialization of an invention created for the market (Li and Atuahene-Gima, 2001)—process innovations are changes in throughput technology (Ettlie and Reza, 1992). This study examines a radical process discontinuity to focus on a fundamental change in foundational throughput technology likely to influence multiple industries.

Two streams of literature provide insight into technological emergence and entrepreneurship after a radical process discontinuity. These literatures examine entrepreneurial opportunity recognition and the role of complementary assets that support commercialization activities. These perspectives are applied to identify which industries are most conducive to entrepreneurial activity after a discontinuity. Next, community-level factors that influence process technology emergence through multiple industries are analyzed.

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Entrepreneurial opportunity

Discontinuities create valuable opportunities that provide entrepreneurial profit, defined as surplus over costs (Schumpeter, 1934). On the surplus side, potential entrepreneurs are more likely to exploit an opportunity when they can perceive potential demand (Choi and Shepherd, 2004). On the costs side, opportunities are more attractive when input costs are lower, for example when the barriers to entry are reduced. Technological discontinuities eliminate some barriers to entry, such as existing scale economies (Yip, 1982) and competency stocks (Henderson and Clark, 1990; Tushman and Anderson, 1986) that would otherwise favor incumbent firms. A reduction in the barriers to entry can attract entrepreneurs with technological know-how (Dean and Meyer, 1996). Thus, technological discontinuities open an opportunity space for new entrants to develop a nascent technology.

A radical technological discontinuity also provides opportunities for entrepreneurs to exploit nascent innovations. Entrepreneurs identify such opportunities through the discovery and creation of knowledge, technology, and ideas (Alvarez and Barney, 2007). It is through entrepreneurs that a nascent technology can lead to new processes, products, innovations, or markets (Shane, 2000). However, potential entrepreneurs must be able to discover or create opportunities to commercialize the new technology to found a firm. Without the identification of opportunities, entrepreneurship is 'fruitless' (Dean and Meyer, 1996: 110; Schumpeter, 1942). And while opportunity recognition may be subjective, an entrepreneur identifies the opportunity and its potential value (Shane and Venkataraman, 2000) or creates an opportunity and exploits it (Baker and Nelson, 2005; Gartner, 1985). Thus, the opportunities must be not only discernible as a viable market business, but also attractive.

Both the opportunity discovery and opportunity creation literatures hold that entrepreneurship starts with a valuable, appropriable idea. Thus, entrepreneurship literature begs the question of what facilitates the recognition of these ideas. The discovery perspective argues that the entrepreneurs have special characteristics that increase the likelihood of opportunity recognition. The creation perspective argues that entrepreneurs explore new products or services. In both accounts, the entrepreneur must take existing knowledge, identify potential market opportunities, and then act upon them.

Knowledge and proximity

Knowledge transfer is facilitated by spatial, technological, and market proximity. The literature on the role of physical or spatial proximity in entrepreneurship argues that geographic closeness facilitates the transfer of knowledge, technology, and organizational routines (Freeman and Audia, 2006). A similar line of research finds that spatial proximity increases the diffusion of ideas such as technology (Phene, Fladmoe-Lindquist, and Marsh, 2006), collective action (Strang and Soule, 1998), and trade unions (Hedstrom, 1994). Thus, spatial proximity provides access to information, ideas, and technology and, in turn, the discovery of entrepreneurial opportunities. These knowledge spillovers are a key mechanism for supporting both new venture formation and economic growth (Agarwal, Audretsch, and Sarkar, 2007). Spatial proximity has also been found to influence the rate of local new firm foundings within an organizational population (e.g., Carroll and Wade, 1991; Lomi, 1995; Sorenson and Audia, 2000; Agarwal *et al.*, 2007).

The related concept of technological proximity, or overlap of firms' research programs, has been shown to interact with spatial proximity such that firms benefit from those knowledge spillovers closest to their own technological space and physical location (Jaffe, 1986). However, Orlando (2004) argued that spatial localization of knowledge may be an artifact of other agglomerative forces. In his study of machinery and computer equipment, Orlando found that technological proximity is more important to the spread of knowledge spillovers than spatial proximity.

Typically, technological proximity has been measured in terms of using the same patent class which is arguably imprecise (Benner and Waldfogel, 2008). However, if we consider technological proximity in broader terms, such as the application of the innovation to an industry or firms that use multiple patent classes, we would expect that technological proximity would support knowledge spillovers. For example, those industries that are technologically close would be more likely to share process knowledge and routines than those that are more distant. Also, technologically close industries develop relationships that facilitate the application of radical process discontinuities. Thus, technological proximity increases knowledge spillovers, which increases the likelihood of entrepreneurship based on a new process technology.

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Work has also shown that knowledge transfer and the founding of new firms increases not only with spatial or technological proximity, but also with market proximity. Interactions between populations in a market or niche provide means for information and knowledge transfer. For example, Audia, Freeman, and Reynolds (2006) applied the community ecology perspective to opportunity recognition, arguing that the structural relationship between populations in a market increases the transfer of information between them, consequently influencing the founding of new firms. They found that the founding rate of instrument manufacturers increases with the increased densities of the populations with which the industry has symbiotic and commensalistic relationships.

Taken together, these studies suggest that the founding of new firms increases with proximity, especially that of technology or market structure. Specifically, in the presence of a radical process discontinuity, entrepreneurship will occur first in those industries most conducive to opportunity recognition and exploitation, such as those technologically closest to or having structural relationships with the technology's origin.

Complementary assets

Research on the role of complementary assets also provides insight into the dynamics between technology emergence and entrepreneurship. Complementary assets are the resources that a firm needs to successfully market a new product or innovation such as distribution, after sales support, and competitive manufacturing (Teece, 1986). These assets are critical to successful market entry (Wernerfelt, 1984) and building sustainable competitive advantages (Dierickx and Cool, 1989). In his seminal work, Teece (1986) described a typology of three complementary assets: general, specialized, and cospecialized. General complementary assets are capabilities and resources that are necessary for commercialization, but are not specific to the product or innovation. Specialized complementary assets are those for which there is a unilateral relationship between the innovation and the asset itself. Cospecialized complementary assets are idiosyncratic to both the innovation and the asset in that each works only with the other.

Each type of complementary asset has its own advantages. For example, general complementary assets are easier to obtain and can be contracted for outside of the firm (Teece, 1986). In such a case, incumbent firms' existing complementary assets are not a barrier for new firms to enter the market since new entrants can easily obtain them on the market. On the other hand, if a technology requires specialized or cospecialized complementary assets, incumbent firms benefit since they have existing access to these complementary assets that are difficult or costly to replicate. During creative destruction, this access can buffer incumbent firms from the threat of new entrants that lack such access (Tripsas, 1997). After a radical technological discontinuity, the performance of the incumbent firm improves when specific complementary assets are required and declines if the new technology requires only generic complementary assets (Rothaermel and Hill, 2005). When the complementary assets necessary to market an innovation are general, access to specialized complementary assets does not provide incumbent firms with a competitive advantage. It follows that new entrants benefit when the innovation being commercialized requires general complementary assets, as the barriers to entry are lower. Thus, nascent technologies that require general complementary assets have lower barriers to entry than those requiring specialized complementary assets, *ceteris paribus*, and will, therefore, have the earliest entrepreneurship.

Synthesis

In summary, previous work has shown that opportunity recognition, knowledge spillovers, proximity, and the type of complementary assets required to market an innovation factor into the founding of new ventures after a technological change. This literature has shown that those industries technologically or structurally close to a discontinuity's origin and those requiring general complementary assets, especially those similar to the nascent technology, have fewer barriers to new entrants than other industries. Considering the trajectories that a technology could follow after a radical discontinuity, it follows that industries that are technologically or structurally close to the technology's origin and require general complementary assets would experience opportunity identification and entrepreneurship earlier than other industries. These characteristics can be found in upstream industries.

Upstream industries are, by definition, those closest to factors of production and raw materials (Porter, 1985; Salinger, 1989). An upstream member of the supply chain provides the raw material inputs needed to create finished goods. As the intermediary between raw materials or technology and the end products, upstream firms create structural relationships with both their suppliers and buyers. In the case of a radical process technology, the supplier to the upstream firm is the origin of the technology. Additionally, upstream firms are technologically closer to a process technology's origins than downstream firms. The technological and market structure proximity of upstream industries to the technology's origin indicate knowledge and information spillovers that may result in entrepreneurial activities.

When a nascent technology can be applied to multiple industries, opportunity recognition is not only a factor for entrepreneurship in the focal industry, but also a factor of the technology's application in other industries. For example, the computer chip industry supplies to the cellular phone, computer, automobile, aircraft, and video game industries, to name a few. A computer chip innovation can be used in a myriad of ways across multiple industries. A more attractive entrepreneurial opportunity based on a radical process technology would be one that has applications across several industries.

Upstream industries provide basic inputs, often to multiple industries that are structurally close. These upstream industries enable the further development of a nascent technology. In line with technology change literature, upstream industries do not require specialized complementary assets since the resources needed to commercialize upstream products are not specific to the technology itself. For example, a technological discontinuity in computer chip manufacturing can be applied across multiple industries, but the complementary assets needed to sell the chip-making equipment will not change. As upstream industries have products that require general complementary assets to market new innovations, it follows that these industries are more attractive to entrepreneurs. Consequently, opportunity identification and complementary assets are most conducive to entrepreneurship in upstream industries after a radical process discontinuity. Thus, after a radical process discontinuity, upstream industries will experience the founding of new firms based on the technology earlier than other industries.

Hypothesis 1: After a radical process discontinuity, entrepreneurship based on the new technology will occur in upstream industries before downstream industries.

Community ecology and industry dynamics

As we have seen, certain radical technologies can be applied to multiple industries. In the previous section, I argue that entrepreneurship based on these technologies will occur first in upstream industries. However, the question remains as to how the entrepreneurship in one industry influences that in others. Work in community ecology provides insight into the relationships between organizations in different populations based on one technology.

Economic entities, such as firms and industries, are embedded in their social context (Granovetter, 1985). A fundamental tenet of community ecology is that the industries within a community, such as those based on the same radical technology, coevolve and directly influence one another (Astley, 1985; Astley and Fombrun, 1987). An example of such industry interdependence is that of new venture coevolution. Van de Ven (1993) argued that the earliest entrepreneurship after a technological discontinuity builds the infrastructure on which entrepreneurship in other populations using the technology relies. This infrastructure includes goods and services that enable the further development of the foundational technology in other industries, particularly those downstream. Therefore, the earliest entrepreneurship in upstream industries builds a foundational infrastructure for those firms in other industries developing the technology.

For the new technology to survive it must gain the legitimacy it often initially lacks. However, new ventures based on a nascent technology contribute to the legitimacy of a new technology (Aldrich and Ruef, 2006) by mimicking organizational structures similar to those common in established and legitimate organizational communities. By using similar structures, these firms display accepted and expected actions (Scott, 2008; Aldrich and Baker, 2001). For example, the online population of retailers often mimics brick-and-mortar retailers by using similar icons and language such as *shopping carts*, where they list products selected for purchase, and *check-out* for the payment and finalization of the purchase. In this way, these retailers gain legitimacy by using forms and practices similar to those in existing retailers. Thus, early entrepreneurship based on a nascent radical technology supports further development of that technology by establishing legitimacy for these organizations.

Studies have shown that the founding rates of populations in a community are interdependent. In

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the microprocessor market (Wade, 1995) and the health care community (Ruef, 2000), researchers demonstrated that firm foundings in new organizational forms are dependent on the density of the entire market, initially increasing with greater market density and then decreasing. Mezias and Kuperman (2000) proposed that an increase in the entrepreneurial activity (higher founding rates) in one population in a community increases the legitimacy and number of opportunities for entrepreneurial activity in another population. The authors supported their predictions using observations from a case study of the emerging American film industry from 1895 through 1929. Lomi (1995) examined the interdependence of two populations in the Italian banking community finding, that as the density of the rural cooperative bank population increased, the founding rate of popular cooperative banks increased. As mentioned earlier, Audia *et al*. (2006) built upon Lomi's study by examining the U.S. instrument manufacturing industry and all industries with which it had symbiotic and commensalistic relationships. They found that the greater the densities of symbiotic and commensalistic populations, the greater the founding rate of instrument manufacturers.

However, the creation of new firms in one industry of a community may not always benefit that in other industries. Hannan and Freeman (1987, 1988, 1989) argued that the environment has a finite carrying capacity for firms and can supply resources to support only a limited number of firms. When an environment's carrying capacity is reached, a firm's ability to obtain sufficient resources decreases. Subsequently, the death rate of firms increases and the founding rate decreases (Hannan and Freeman, 1989). Similarly, firms that compete for the same set of resources (i.e., those in commensalistic industries) will not be able to obtain resources, and the founding rates of new firms in these industries will also decrease. Therefore, entrepreneurship based on a radical process discontinuity in upstream industries will have a curvilinear relationship with that in downstream industries, such that the number of firms founded in downstream industries will first rise and then fall with the increase of firms in upstream industries.

Hypothesis 2: After a radical process discontinuity, as the number of new ventures founded in upstream industries increases, the number of firms founded in other industries using the nascent technology increases. At a point, however, a further increase in the number of firms founded in upstream industries will lead to a decrease in the number of firms founded in other industries using the nascent technology.

DATA AND METHODS

The setting of this study is the emergence of nanotechnology in the United States. Nanotechnology is the research and development of materials and products that have a size between one and 100 nanometers (National Science and Technology Council, 2000), with applications in nearly every industry, ranging from semiconductors to optics and biotechnology (National Nanotechnology Coordination Office, 2007). Nanotechnology is not simply the art of taking existing items and shrinking them down to a smaller scale. The physics and properties of matter change at the nanoscale, and its development requires a multidisciplinary approach that produces wide-reaching breakthroughs.

Nanotechnology has been part of the scientific imagination since 1959 when Nobel laureate Dr. Richard Feynman asserted that—while not possible at the time—scientists would be able to create machines at the molecular scale (Feynman, 1959). It was not until 1974 that the word *nanotechnology* appeared in print when Norio Taniguchi of Tokyo Science University used it to refer to 'production technology to get the extra high accuracy and ultra fine dimensions, i.e. the preciseness and fineness on the order of one nm (nanometer), 10^{-9} meter in length' (Taniguchi, 1974: 18). During the 15 years since Feynman's presentation, very few researchers addressed the possibility of manipulating at the nanoscale, and most considered the idea an impossible dream. In fact, a debate existed in the scientific community as to the possibility of nanoscale manipulation. Even at the time the term was coined, nanotechnology did not exist, as equipment could neither manipulate nanoscale material nor magnify matter at the nanoscale to visibility.

In 1981, the debate was resolved with the invention of the scanning tunneling microscope (STM) by Gerb Binnig and Heinrich Rohrer at IBM. The invention of STM was essential for the progress of nanotechnology, as it is the first instrument that enabled scientists to see and manipulate at the nanoscale. In 1987, Binnig and two colleagues, Christoph Gerber and Calvin Quate (also at IBM), invented the atomic force microscope (AFM). The

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AFM enabled scientists to see a three-dimensional representation of the sample surface at the atomic (nano) level, which was not possible previously; this marked the start of nanotechnology.

Incumbent firms were critical to the research and development of nanotechnology. IBM was a forerunner in the field, with research starting in the 1970s that resulted in numerous patents through the 1980s and beyond—including both the STM and the AFM. Today, IBM holds the highest number of nanotechnology-related patents in the world. Other incumbent firms heavily active in early nanotechnology R&D include NEC, Hitachi, RCA, Honeywell, and Motorola. However, the patent and product records of incumbents indicate that they generally did not commercialize their nanotechnology inventions, but used them internally for further R&D efforts and sustained innovation. If they did license their technology, it was usually to start-up firms. For instance, commercialization efforts for the STM (patented in 1981) did not start until 1987, after the inventors were awarded the Nobel Prize in Physics in 1986 and one of Japan's government labs announced their own invention of a competing STM. IBM's commercialization efforts for the STM and AFM resulted in licenses to two start-up firms, Digital Instruments (U.S.) and Omicron (Germany). Similarly, NEC invented nanofilms in 1987 and the carbon nanotube in 1991. While it appears that NEC incorporated the nanofilms as a component into their other products, the firm licensed the carbon nanotube patents to start-up SouthWest NanoTechnologies, Inc. It is through start-ups that these inventions reached the market. While incumbent firms played a role in the creation of nanotechnology, they were not key in its commercialization. Thus, this study focuses on the commercialization efforts of new firms and the key role they played in technology emergence.

When studying a process, researchers 'often have difficulty in identifying discrete points of origin' (Aldrich and Ruef, 2006: 181). To overcome this difficulty, I collected data from the earliest conceptualization of nanotechnology in 1959 through 2005. This ensures that the data are not left censored, whereby the origins of an event occur before the opening of the observation window (Yamaguchi, 1991; Blossfeld and Rohwer, 2002). In this case, all nanotechnology firm foundings occur after the beginning of observations in 1959. While left censoring is a limitation of many organizational studies, a strength of this study is that the data collection includes the earliest history of the nanotechnology industries.

Data sources

To gain a full history of nanotechnology's emergence, several sources of archival data—including industry lists, directories, press releases, publications, and web sites related to nanotechnology—were compiled. A master list of nanotechnology firms was compiled from these sources. Lists and directories were located by searching the Internet and print journals for associations, groups, or organizations supporting nanotechnology firms. Theses searches yield six such organizations: (1) Nano Science and Technology Institute (NSTI); (2) NanoInvestorNews and (3) NanoMarkets, which are two U.S. market research firms specializing in the nanotechnology markets; (4) NanoTechWire and (5) Small Times Media, both of which gather data on new and existing nanotechnology firms for its members; and (6) the Foresight Institute, a think tank founded to promote nanotechnology education for society. These resources obtain data directly from organizations in the nanotechnology community. Data from these sources were aggregated into a database on nanotechnology firms. This database was augmented with new firms listed in a search for nanotechnology in PR Newswire and Price WaterhouseCoopers' venture capital Web site. Duplicate listings were eliminated, resulting in a final list of 1,682 firms. Each firm was analyzed to determine if it fit the criteria for being a nanotechnology firm: single-business ventures founded to develop, produce, and sell nanotechnology products on the merchant market. Specifically, firms must have more than 50 percent of their activities,[1] such as products, R&D, or sales, derived from or related to nanotechnology. By this definition, captive producers, divisions, and spin-offs of existing firms, distributors, designers, and custom engineering firms were excluded from the study. Software, investing, and consulting firms were also excluded. Of the firms that claim participation in the nanotechnology community, many do not operate at the nanoscale. To truly be a nanotechnology firm, the

[1] As some new firms either had no sales or financial data was not available, I examined the products available or under development for evidence of nanotechnology activity. Firms were included in the study if more than 50 percent of their products were derived from nanotechnology.

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Table 1. Description of industries involved in nanotechnology and their products

Industry	Description	Products	Example firm
Biotechnology	Applications to label, detect, and study biological systems	Nanoscale biological assays	BioForce Nanosciences
Electronics	Create devices and components at the nanoscale	Nanotube-based nonvolatile RAM	QD Vision
Energy	Use nanotechnology to produce or store energy	Nanocarbon-based fuel cell components or solar cells	mPhase Technologies
Instrumentation	Produce technical devices used to see and manipulate at the nanoscale	Scanning electron microscopes, nanoimprint lithography instruments	Omniprobe
Materials	Purposefully engineer structures of matter with a dimension of less than 100 nanometers exhibiting size-dependent properties (Lux Research, 2004)	Encapsulated titanium particles of 20 nm diameter	Applied NanoMaterials Inc.
Medical devices	Application of nanotechnology to medical devices and products	Osteoconductive bone regenerative tissue	Angstrom Medica Inc.
Optics	Develop integrated, *subwavelength* optical communications components	Atomic holographic optical data storage nanotechnology	NeoPhotonics Corporation
Pharmaceuticals	Application of nanotechnology to the delivery of pharmaceuticals in the human body; develop new drugs	A nanoscale coating for drugs to slow or improve the release of an active component	NanoTrope
Semiconductors	Apply nanotechnology to the production of semiconductors	System-on-chip using 90 nanometer integrated circuits	eASIC
Other	Not classified above	Consumer products such as sporting goods	NanoSafeguard

technology used must be less than 100 nanometers. Unless the firms utilize technology to manipulate components at the nanoscale, they are not considered nanotechnology firms and are excluded from the study. Therefore, the identification of nanotechnology firms was an extensive process. Firms with nanoscale capabilities were identified by their product, patent, and technology data. This study's final list of nanotechnology firms was compared to that of a colleague[2] who had undertaken a similar process to identify nanotechnology firms. While the identification techniques were not identical, our databases overlapped by almost 90 percent. Any firms not included in my database were examined using the previously identified criteria for nanotechnology firms. No additional firms met the criteria, as they were: (1) firms proposing to use nanotechnology, but unsuccessful; (2) software modeling firms; or (3) firms using microlevel technology, but not nanoscale. Thus, the database was not augmented. In total, 306 nanotechnology firms (about 18% of the original list) were founded in the United States between 1987 and 2005.

The database includes firm demographic data including location, founding date, and date of business cessation (indicated by dissolution, bankruptcy, merger, or acquisition), if applicable. The location of the headquarters was verified by the firm's Web site and Dun and Bradstreet listing. The industries in which these firms operate were determined from Dun and Bradstreet, Hoover's, and NAICS listings. If these data were not available (102 cases), additional data were used to identify the appropriate industry. Products, product descriptions, and additional industry data, such as buyer industries, were collected when available. Table 1 provides a description of each industry in which the firms operate, examples of products, and a representative firm.

[2] I gratefully acknowledge the collaboration of J. Wang on this task.

Upstream industries are those closest to raw material, supplying basic goods and services to other industries. To identify the upstream industries using nanotechnology, a map of the industries using nanotechnology was created from the archival and interview data. First, the nanotechnology firm data identified to which industry each firm supplied. Table 2 shows the resulting buyer-supplier matrix, with a 1 if the relationship exists for more than two firm cases, and a 0 if it does not. Second, Figure 1 was constructed to depict the relationships between the industries. A directional line connects each industry with that to which it supplies. For instance, the biotechnology industry supplies to the pharmaceutical and medical industries. From this analysis, two upstream industries emerged: instrumentation and materials with eight and seven buyer industries, respectively. The identification of the upstream industries was supported by a Lux Research report (2004),[3] which identified two industries as highest on the nanotechnology supply chain: materials and instruments.

Additional analysis of the nanotechnology industries indicates that non-upstream firms rely on these upstream firms. Each of the non-upstream industries must use materials or instrumentation in the development or manufacturing of their products. For example, nanotechnology electronics firms use materials as the basis for nanoscale components in devices and use instrumentation to etch patterns less than 100 nanometers. In summary, without firms in the materials or instrumentation industries, technological innovation in other industries of the nanotechnology community would not be possible.

Given the extensive search for all new nanotechnology firms founded through multiple sources dedicated to the nanotechnology community, it is probable that nearly all new nanotechnology firms have been captured in this database. However, if the founders of a new nanotechnology company were not involved in the nanotechnology community, elected not to expose their existence, and were not known to others in the community, this firm would not be discernible and not be included in this search. As the nanotechnology community is highly science based and there are very few people with the substantial knowledge of nanotechnology needed for a commercial endeavor, it is unlikely that a firm would remain undetected by others in the community.

Table 2. Up- and downstream markets in nanotechnology by industry

		Buyer										
		Instrumentation	Materials	Biotechnology	Semiconductors	Optics	Energy	Pharmaceuticals	Medical devices	Electronics	Consumer products	Downstream markets
Supplier	Instrumentation		1	1	1	1	1	1	1	1	0	***8***
	Materials	0		1	1	1	1	1	1	1	0	***7***
	Biotechnology	0	0		0	0	0	1	1	0	0	***2***
	Semiconductors	0	0	0		0	0	0	1	1	0	***2***
	Optics	0	0	0	0		0	0	0	1	0	***1***
	Energy	0	0	0	0	0		0	0	0	1	***1***
	Pharmaceuticals	0	0	0	0	0	0		0	0	1	***1***
	Medical devices	0	0	0	0	0	0	0		0	1	***1***
	Electronics	0	0	0	0	0	0	0	0		1	***1***
	Upstream markets	**0**	**2**	**2**	**2**	**2**	**2**	**3**	**4**	**4**	**4**	

[3] Lux Research is the first firm founded to research nanotechnology commercialization.

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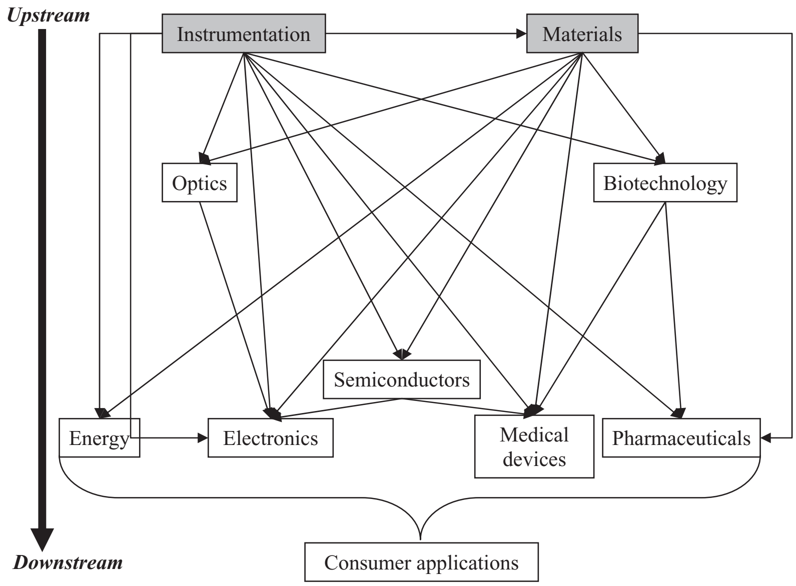

Figure 1. Interdependence of industries using nanotechnology

Variables

Dependent variables

The dependent variable for Hypothesis 1 is the time to firm founding. The variable was measured in terms of the number of years after 1985 in which the firm was founded (chosen since no nanotechnology firms were founded before this year).

The dependent variable for Hypothesis 2 is the number of downstream nanotechnology firms founded, measured annually through 2005. In testing the relationship between the densities of upstream industries and density of other industries in the community, it is important to not include upstream firms in the dependent variable. The number of firms in the upstream industries—materials and instrumentation—was subtracted from the total number of firms.

Independent variables

The independent variable for Hypothesis 1 is the firm's industry. Dummy variables for each industry were calculated, as well as a dummy for upstream industries (firm belonged to either materials or instrumentation industries) and one for downstream industries (firm belonged to neither materials nor instrumentation industries). This enabled not only downstream versus upstream models to be constructed, but also industry specific models to test the nuances of each.

The independent variables for Hypothesis 2 are the number of firms founded in the upstream industries. I used three measures for the number of firms founded in upstream industries: (1) the number of materials firms founded; (2) the number of instrumentation firms founded; and (3) the number of both materials and instrumentation firms founded, each measured annually. Since firms founded in December of 1995 would have little time to influence firms founded in other industries by January of 1996, the variables were lagged two years. All independent variables for Hypothesis 2 were standardized.

Controls

The founding rates of populations in the nanotechnology community may be reflective of firm founding trends in the environment. To control for this relationship, the models include the number of new firms founded in the United States each year, obtained from the Small Business Administration and the Internal Revenue Service, along with the square of this variable to control for curvilinear effects.[4] Institutional theorists and organizational ecologists argue that environmental munificence influences the founding of new firms (Van de Ven,

[4] The Small Business Administration (2006) defines a firm as 'an aggregation of all establishments owned by a parent company with some annual payroll.'

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1993; Aldrich and Ruef, 2006). To control for this relationship, the models include a measure of environmental munificence: the annual U.S. federal government spending on nanotechnology research and development (R&D) obtained from the National Nanotechnology Institute (which documents annual spending by U.S. government agencies on nanotechnology). As an additional control for economic fluctuations, I included the value of the NASDAQ Index at year end.[5] Lastly, the density of downstream firms was controlled as well.[6] All control variables were taken at a two-year lag and standardized.

Analysis

Three methods were used to analyze the data: historical analysis, event history analysis, and multivariate regression. Historical analysis is a process by which longitudinal data are organized chronologically by year and their relationship to other data points is examined. This research takes the form of what Ventresca and Mohr (2002: 810) call 'the New Archival tradition,' a body of work that relies on formal analytical methods, examines social organizations and its elements instead of organizations themselves, emphasizes the study of relationships, considers the shared forms underlying processes, and studies the *configurational logics* that bind elements into collective activity. Sequences and patterns in the data emerge, leading to a picture of the phenomenon over time. In the historical analysis of the nanotechnology data, I explore the timing of the first nanotechnology firm foundings and their structural relationships.

Hypothesis 1 was also examined using event history analysis of the nanotechnology data for the time to founding. The models predicting time to firm founding were estimated by the log-normal model using STATA. The log-normal model takes the form (Allison, 1984):

$$\log t = X\mathrm{B} + \log t_0 \qquad (1)$$

[5]An additional control for environmental munificence and economy—annual venture capital funding—was tested. Venture capital funding was excluded from the estimations, as it was highly correlated (r = 0.97) with U.S. federal funding of nanotechnology and VC funding of nanotechnology started four years after federal funding.

[6]The author is indebted to the anonymous reviewers for the advice to include the NASDAQ Index and downstream firm density as controls.

where t is the time duration, X is the vector of coefficients for the covariates (B). Since firm foundings are repeatable events (e.g., firms are founded in different years within one industry), the time between foundings is valuable data. To retain the information provided by each firm's founding, episodes were constructed in STATA at each event (or firm founding) using the *stsplit* command, which calculates the time to first founding in the industry and then the time between foundings.

To model Hypothesis 2, I used longitudinal, pooled cross-sectional data for each industry in the nanotechnology community over time from 1987 through 2005. The data are time series, defined as a sequence of observations which are ordered in time, $x_1, x_2, \ldots, x_t$, where the interval between two successive observations, t and t + 1, is fixed and constant, being one year (Malinvaud, 1980). The data were gathered for each year and no data are missing, which creates a *balanced panel* of data (Yaffee, 2003). The panel is comprised of count data. The models predicting the founding rates of nanotechnology materials and instrumentation industries are estimated by time series negative binomial regression model estimation, fixed effects for year variance. The model takes the form (Greene, 2003: 745):

$$f(y_i|x_i) = [\Gamma(\theta + y_i)/\Gamma(y_i + 1)\Gamma(\theta)]r_i^{y_i}(1 - r_i)^{\theta} \qquad (2)$$

$$r_i = \lambda_i/(\lambda_i + \theta) \qquad (3)$$

where y_i is the number of the dependent variable at time i, θ is the overdispersion parameter, and λ_i is the conditional mean. The conditional variance is:

$$\lambda_i[1 + (1/\theta)\lambda_i]. \qquad (4)$$

RESULTS

As mentioned, it was not until 1987 when the first firm, Digital Instruments, was founded to specifically exploit and dedicate the majority of its activities (more than 50% of R&D, expenses, or revenue) to nanotechnology. Although IBM and other firms were conducting basic research related to nanotechnology in the early 1980s, no firm identified the majority of its activities as related to nanotechnology before 1987. Therefore, only firms founded from 1987 to 2005 are included in this analysis. Of the 306 firms identified in the archival data, 30 firms

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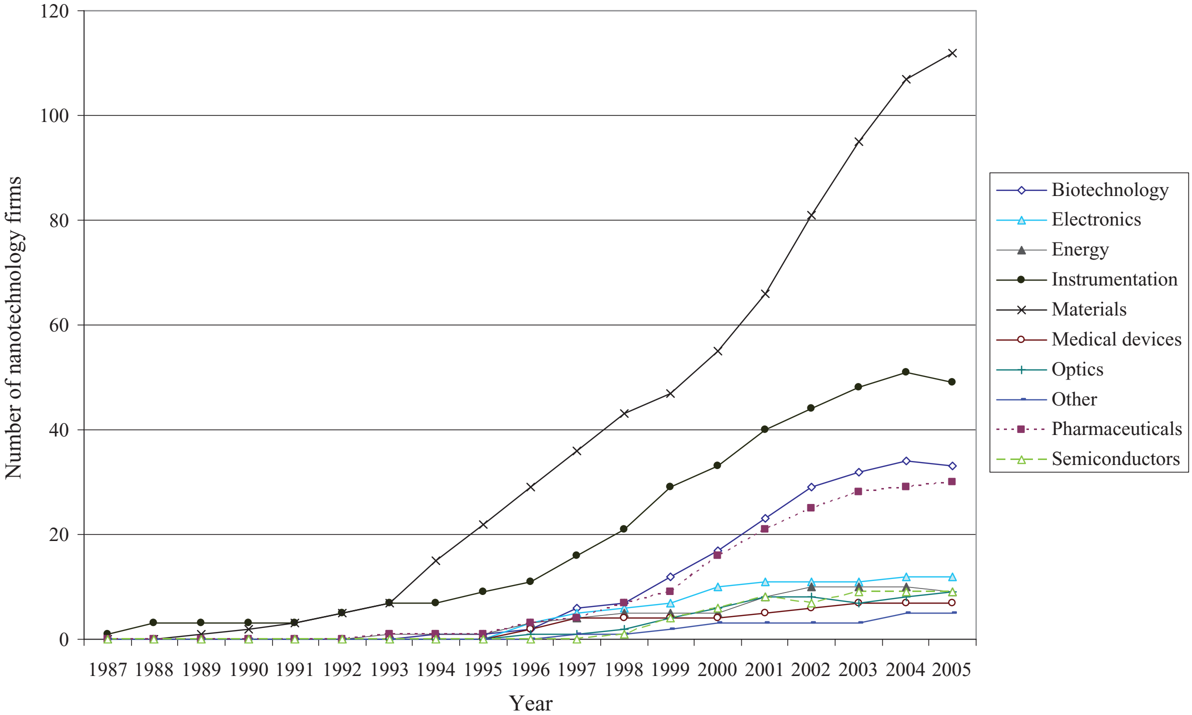

Figure 2. The density of nanotechnology firms by industry and year, 1987–2005

ceased to exist, resulting in a living population of 276 firms by the end of 2005.

Hypothesis 1 argues that entrepreneurship based on a radical process technology will occur first in upstream industries. The historical analysis of the data supports this hypothesis. Figure 2 shows the number of nanotechnology firms operating in each industry (y-axis) for each year (x-axis) from 1987 through 2005. The figure shows that from 1987 to 1990, instrumentation was the largest population, indicated by the solid line with dark circles. It is not clear from the figure which of the other industries was the second to add firms. Analysis of the numerical data shows that the second-largest population was that of materials. In fact, instrumentation and materials industries had the same number of firms alive from 1990 to 1993. After 1993, the density of the materials population increased to become the largest, as shown in Figure 2 by the line with X's, while the instrumentation population was second. These two industries are those identified previously as upstream industries. The historical analysis shows that these upstream industries had the highest number of firm foundings and overall densities during the entire research period.

Figure 3 further illustrates the difference in the number of firms in upstream versus downstream industries. The total number of upstream firms is depicted by a solid line with squares and the number of downstream firms is shown by a dark line with diamonds. It is evident that very few nanotechnology firms were founded outside of the two upstream industries before 1996. In fact, the total number of downstream firms jumped from three in 1995 to 14 in 1996, 25 in 1997, and 33 in 1998. Even with this quick movement of other industries into the community, the number of materials and instrumentation firms exceeds that in other industries throughout the emergence of nanotechnology.

To examine Hypothesis 1 further, a series of event history analyses was performed. Table 3 shows the mean, standard deviation, and correlations for each variable. From 1985 to 2005, an average of 868,000 new firms were founded in the U.S. each year. During the same time period, the U.S. federal government spending on nanotechnology grew from $0 to $1.1 billion, with an average of $262 million each year. The matrix reports high correlations among the density variables and firm founding variables. Close variable dependencies may degrade parameter

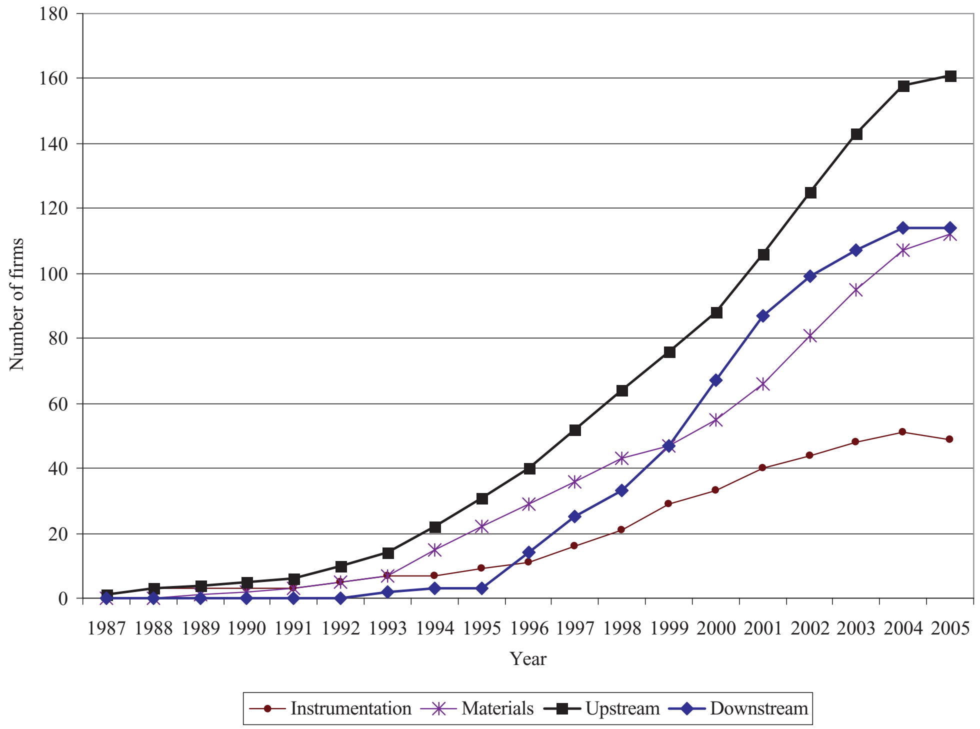

Figure 3. The density of upstream and downstream nanotechnology firms by year, 1987–2005

Table 3. Mean, standard deviations, and correlation matrix[a]

		Mean	S.D.	1	2	3	4	5	6
1	Downstream firms founded	12.37	5.86						
2	New U.S. firms (1,000)	867.81	41.76	0.74					
3	U.S. federal nano funding (MM)	262.16	360.09	0.05	0.44				
4	Density of downstream industries	67.29	38.67	0.36	0.65	0.94			
5	NASDAQ Index	1987.45	785.10	0.38	0.55	0.11	0.20		
6	Materials firm foundings	9.73	4.13	0.32	0.42	0.65	0.75	−0.22	
7	Instrumentation firm foundings	5.01	2.18	0.64	0.73	0.08	0.28	0.56	0.22

n = 306 firms.
[a]Correlations greater than 0.11 are significant at $p < 0.05$.

estimates by inflating standard errors without necessarily harming them in hypothesis testing (Belsley, Kuh, and Welsh, 1980). Specifically, if the test examines the sign of the coefficient and it is shown to be significant as hypothesized while including collinear variables, the close variable dependencies have not harmed the parameter estimates (Belsley *et al.*, 1980). Although the confidence intervals may be increase, collinearity has caused no harm to the model, which would be indicated if results were inconsistent.

Table 4 presents the results of the event history analysis for Hypothesis 1 with Model 1 including only the controls. Model 2 includes values for each of the upstream industries individually, which significantly improves the fit of the model ($p < 0.01$). As shown, the models support the hypothesis that entrepreneurship based on a nascent radical process

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Table 4. Event history analysis of the time to founding (lognormal)[a]

Variables	1		2	
	Coeff.	S.E.	Coeff.	S.E.
Materials∧			0.014	(0.015)
Instrumentation∧			–0.058***	(0.018)
New U.S. firms	0.334***	(0.015)	0.336***	(0.015)
New U.S. firms squared	–0.129***	(0.012)	–0.132***	(0.012)
U.S. federal nanotech funding	0.105***	(0.010)	0.103***	(0.009)
Constant	2.526***	(0.012)	2.534***	(0.014)
Log-likelihood ratio	213.931		221.61	
χ^2	543.68***		559.04***	

[a] All independent variables have been standardized.
Values are regression coeffiecients with standard errors in parentheses.
Number of oberservations for all models is 4,001.
∧ Compared to downstream industries.
*p < 0.05, **p < 0.01, ***p < 0.001.

discontinuity occurs in upstream industries before in downstream industries, but only in the instrumentation industry, not in the materials industry.[7] Model 2 shows that for nanotechnology firms, being in the instrumentation industry reduces the time to founding compared to that of other industries. However, this is not the case for those in the materials industry. Patent data provides insight into these results. First, from 1981 to 1989, the vast majority of nanotechnology-related patents in the U.S. are related to scientific instrumentation, especially measuring devices. This indicates that most of the early innovation in nanotechnology took place in the instrumentation field. Second, basic scientific instrumentation is often necessary for the creation of nanoscale materials (see Figure 1). Specifically, many of the early nanotechnology patents related to materials cited the particular scientific instruments (and their patents) used to invent and measure the material. This indicates that for early materials innovations and R&D, basic instrumentation innovations must occur first and be commercially available. Therefore, although the instrumentation and materials industries are upstream to most other industries in the nanotechnology area, the structure of the relationship between the industries leads to instrumentation innovation and entrepreneurship occurring first.

Table 5 presents the results of the regression analyses for Hypothesis 2 with Model 3 as the base model with only control variables. First, models include linear variables only (models 4, 6, and 8), followed by models with the squared terms for each independent variable (models 5, 7, and 9). Each model with the squared term is a significant improvement over linear models ($p < 0.001$ using the X^2 test). The models support Hypothesis 2 such that the number of firms founded in upstream industries has an inverted-U shaped relationship with the number of firms founded in other industries, but for materials firms, not instrumentation. Models 4 and 5 use the additive function of the two upstream industries. Figure 4 graphically depicts this relationship with the number of upstream firms founded on the x-axis and the number of downstream firms founded on the y-axis. It is interesting to note that the relationship between the variables did not appear until a critical mass of about 14 upstream firms had been founded, which did not take place until after 1995, eight years after the first nanotechnology firm was founded.

As a further test, Models 6 and 7 include the number of firms founded in the materials industry, showing that as the number of firms founded in materials industries increases, the number of firms founded in downstream industries using the nascent technology also increases, until a point at which the trend reverses. Models 8 and 9 include the number of firms founded in the instrumentation industry. Surprisingly, these models show that as the number of nanotechnology instrumentation firms founded increases, the number of firms founded in downstream industries using the nascent technology decreases until a point at which the trend reverses,

[7] Similar results were found with models for each industry separately, including each downstream industry. A model with all industries, except materials, also indicated the same results.

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Table 5. Fixed effects negative binomial regression analysis for the influence on downstream industries' foundings[a]

Variables	3	4	5	6	7	8	9	10
Upstream foundings[b]		0.573***	4.261***					
		(0.082)	−0.342					
Upstream foundings—squared			−3.939***					
			(0.336)					
Materials firm foundings				1.077***	4.870***			5.700***
				(0.113)	(0.383)			(0.451)
Materials firm foundings—squared					−6.097***			−7.415***
					(0.120)			(0.636)
Instrumentation firm foundings						−0.031	−0.827***	−0.261
						(0.047)	(0.140)	(0.237)
Instrumentation firm foundings—squared							0.769***	0.498*
							(0.126)	(0.205)
New U.S. firms	1.039***	0.533***	−0.465***	0.682***	−0.486***	1.070***	1.524***	−0.617**
	(0.067)	(0.099)	(0.128)	(0.075)	(0.128)	(0.081)	(0.123)	(0.236)
New U.S. firms squared	−0.227***	−0.267***	0.504***	−0.118**	0.043	−0.213***	−0.528***	−0.257**
	(0.041)	(0.041)	(0.074)	(0.044)	(0.047)	(0.045)	(0.072)	(0.102)
U.S. federal nano funding	0.065	−0.450***	0.616***	−0.640***	3.476***	0.091	−0.017	4.041***
	(0.075)	(0.107)	(0.135)	(0.107)	(0.387)	(0.085)	(0.089)	(0.425)
NASDAQ Index	0.113***	0.271***	0.049	0.694***	0.346***	0.122***	0.028	0.129
	(0.020)	(0.030)	(0.732)	(0.063)	(0.078)	(0.024)	(0.029)	(0.127)
Density of downstream industries	−0.475***	−0.230*	−0.642***	−0.642***	−1.757***	−0.510***	−0.348***	−1.604***
	(0.087)	(0.097)	(0.098)	(0.089)	(0.135)	(0.101)	(0.108)	(0.142)
Constant	1.791***	2.330***	1.777***	1.848***	0.809***	1.737***	1.831***	1.066***
	(0.070)	(0.104)	(0.114)	(0.071)	(0.120)	(0.107)	(0.112)	(0.142)
Log-likelihood	−781.938	−759.450	−677.356	−723.124	−661.307	−781.711	−761.245	−642.571
X^2	464.60***	513.58***	673.77***	582.23***	705.86***	465.06***	505.99***	743.34***
R^2	0.229	0.253	0.332	0.287	0.348	0.2293	0.249	0.367

[a]All independent variables have been standardized.
[b]Upstream industries includes materials and instrumentation firms.
Values are regression coefficients with standard errors in parentheses. Number of observations for all models is 5,814.
*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

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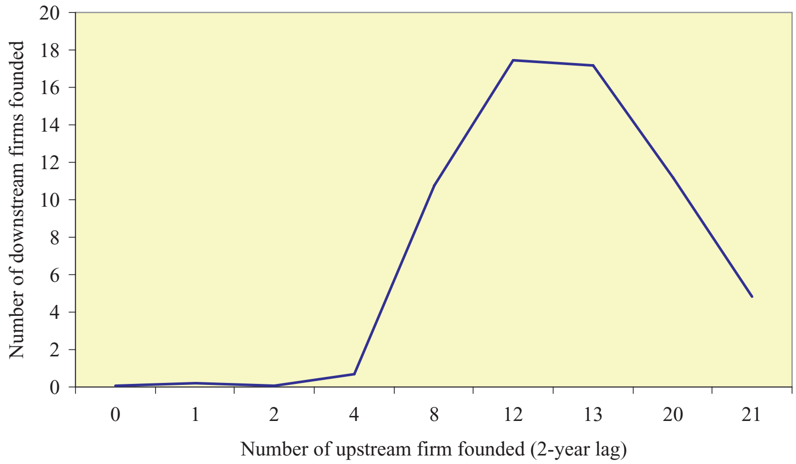

Figure 4. Analysis of upstream firm foundings on downstream firm foundings

opposite to expectations. Model 10 shows these covariates together and shows that the nanotechnology materials firm foundings are more consistently significant than those in the instrumentation industry; however, the shape of the relationships remains.

While these findings are surprising, a number of market dynamics may explain the results. One explanation involves unobserved heterogeneity of incumbent firm actions.[8] It may be that the incumbent instrumentation firms were able to adapt and innovate to meet the new needs of nanotechnology customers, thus leading to fewer new firms being founded. Alternatively, the combined commercialization efforts of instrumentation incumbents and new entrants may have met the market needs. In either case, the findings from Hypothesis 1 and Figures 2 and 3 show that instrumentation enjoyed an initial jump in firm foundings, but then grew more modestly compared to materials firms and downstream firms, especially after 1995. As such, the U-shaped relationship between new instrumentation firms and new downstream firms is reasonable.

DISCUSSION

The objective of this study is to enhance our understanding of technology emergence by examining two neglected contexts: entrepreneurship after a radical process discontinuity and a technology that is used across multiple industries. The results demonstrate that after a discontinuity, a process technology first emerges through entrepreneurship in upstream industries, primarily in those industries providing instrumentation, but not materials, to other firms. It was hypothesized that the founding of firms in these upstream industries had an inverted-U shaped relationship with the founding of firms in other industries using the nascent technology. However, the results show that in nanotechnology only one of these upstream industries—materials—had such a relationship. As described, this may be due to the market dynamics of instrumentation firms with downstream industries. This may also indicate that entrepreneurs identify more attractive and profitable opportunities in the materials industry than in the other upstream industry of instrumentation. Alternatively, it may be that in nanotechnology, materials firms are more fundamental to the overall development of the technology and new entrepreneurial opportunities downstream. While new instrumentation firms appeared first, opportunities were identified for materials firms and the number of these firms increased significantly. These findings may indicate a step-wise progression in technology emergence such that first instrumentation is built that uses the nascent technology. Then new opportunities are identified or created based on the new capabilities arising from the instrumentation. A more in-depth analysis of nascent process technology emergence is needed to more clearly understand these dynamics.

Given these results, the question remains as to how technological and market proximity would

[8] I thank the anonymous reviewers for calling attention to this issue.

influence each industry independently. Specifically, how do the firm foundings in all of the industries upstream to one industry influence the foundings in that particular industry? One would expect an inverted-U shaped relationship based on the earlier theoretical arguments and the findings here. Unfortunately, the data compiled here are not sufficient to answer this question, as the number of firms founded each year in some industries alone is fairly small. However, this would be a fascinating area for future inquiry.

This study builds on and extends our current understanding of technology emergence. First, I examine a wide-ranging technology that emerges in several industries, thereby going beyond technology emergence studies focused on one industry. By including all relevant industries, we gain insight into the earliest emergence of the technology and the interaction of the industries in which it develops. While this study focuses on radical process discontinuities, it is relevant to other fundamental innovations that influence multiple industries, such as radical product discontinuities of a fundamental or platform technology.

Second, the study examines the temporal dynamics of emergence by examining entrepreneurship based on a technological discontinuity across 19 years. Here we see that the earliest entrepreneurship based on a discontinuity shapes the direction of the technology's emergence. Consistent with the community ecology tenet of industry interdependence, these findings show that the existence of upstream industries based on a technology will benefit other industries with the same technological foundation (Astley and Fombrun, 1983). Incorporating our understanding of knowledge spillovers indicates that how a technological discontinuity is developed in the earliest upstream industries shapes the trajectory of its further development (Giarratana, 2004). This would follow the push perspective of technology development (Dosi, 1982). However, the interaction between upstream firms and potential entrepreneurs may be more intricate. Mowery and Rosenberg (1979) argue that it is the combination of both technology push and demand pull that drives innovation and provides economic incentives for technology change and commercialization. This argument supports the different results for materials and instrumentation industries. An in-depth analysis of the dynamics between upstream and downstream industries is essential to the further understanding of how technology emergences across industries.

The study also finds support for the predictions that entrepreneurship in one industry can provide opportunities for entrepreneurship in other industries in a community (Mezias and Kuperman, 2000). This research shows that not only are industries' entry rates interdependent, but also that the timing of industries' entry after a discontinuity influences the technology's development. Thus, this research extends the community ecology perspective and technological discontinuity literatures, as well as contributes to our understanding of technology emergence across industries.

Radical innovations can be both competence destroying, requiring new skills, abilities, and knowledge, and competence enhancing (Gatignon *et al*., 2002; Tripsas and Gavetti, 2000). As with other technologies, such as digital imaging, nanotechnology can be competence enhancing to one firm while competence destroying to another. Gatignon (*et al*., 2002: 1107) argue that 'literature on competence enhancing/destruction is unclear on units of analysis,' which gives rise to confusion in considering the influence of an innovation. As such, one may argue that nanotechnology can be competence enhancing to one industry while competence destroying to another. This implies a more complex dynamic between industries in a technological community that provides another avenue for further research.

The study has implications for practicing managers and entrepreneurs. Here we see that the initial opportunities identified and acted upon by entrepreneurs after a technological discontinuity are those in upstream industries. This implies that first, entrepreneurial opportunity recognition is influenced by technological and market relationships, as well as the complementary assets necessary for commercialization. While the study does not identify specific mechanisms by which entrepreneurs weigh these inputs, it does indicate that enhanced discernment abilities to evaluate inputs may improve an entrepreneurs' ability to recognize attractive opportunities. Especially after a radical process discontinuity, opportunity recognition in upstream industries is fundamental in the future trajectory of the technology's emergence and other entrepreneurial opportunities.

A second implication for entrepreneurs is underscoring the importance of identifying the upstream inputs necessary for technology development and understanding the needs of downstream industries which provide multiple avenues for technology appropriation. This knowledge can improve the

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positioning of a firm during technology emergence, especially in terms of providing products and services to meet an emerging, yet underserved, demand. Another opportunity exists for those in downstream industries that can develop these technologies. Firms can gain first-mover advantages by working with upstream firms early to develop a nascent technology. Entrepreneurs or incumbent firm managers who identify nascent technology applications consistent with their current access to complementary assets can benefit by leveraging their existing value chain.

A third implication for entrepreneurs is the possibility of opportunity creation in addition to discovery (Alvarez and Barney, 2007). At several points in the emergence of nanotechnology, entrepreneurs could have created new opportunities that would have changed the landscape of the field. After a radical technological discontinuity, entrepreneurs can venture into new areas based on the breakthroughs that did not previously exist. At the same time, discovery-oriented entrepreneurs can focus their search activities on areas of technological and market proximity, which may prove fruitful for leveraging spillovers. In both cases, entrepreneurs must take into account the changing and uncertain environment after a discontinuity. More importantly, entrepreneurs seeking to create or discover an opportunity after a technological discontinuity should not focus on the industry in which the technology arises. As seen here, entrepreneurship in one industry can provide fodder for entrepreneurship in others.

Policymakers can also benefit from the results of this study. Since entrepreneurship of an emerging technology occurs first in upstream industries, those supporting an emerging technology should first look to support the most elemental of inputs. Those policymakers seeking to build an emerging technology cluster should first foster the development of upstream firms to build the infrastructure necessary for the technology's integration into other industries, as well as supporting industry interactions to facilitate knowledge spillovers. While these firms may not be traditionally associated with an emerging technology (such as materials firms), the opportunities are critical to the founding of other technology firms and further economic development.

Although these analyses provide insight into technology emergence, this study is not without limitations. Nanotechnology firms have been in existence for a relatively short amount of time. While historical accounts of technology development (e.g., Chandler, 1962; Reader, 1975; Cusumano, Mylonadis, and Rosenbloom, 1992) are useful in the general sense, these do not provide the fine-grained analysis needed for further theory development. Research using a longer span of data will inevitably provide additional insight into the process of technology emergence and industry interdependence. A particularly attractive avenue for future research is to examine the factors influencing the success of these firms across industries over time.

Overall, the results suggest that nascent technology is built on the foundation of upstream industries that provide tools and materials, which enable its further development; however, these industries operate in different ways. Here we see the importance of upstream industries as pivotal to the direction of technology emergence. Other industries in which the technology is used benefit from the foundation of these upstream industries. However, the dynamics are not simply a story of market proximity or value chain flow. Case studies of the interactions between these firms would further illuminate this area.

Furthermore, the results show an interaction between the founding of materials firms and the control variable of overall firm foundings in the U.S. In the models including materials firms and the square of this figure (Models 5, 7, and 9), the direction of the relationship between U.S. firms founded and downstream firms founded changes from inverted U-shaped to U-shaped while remaining significant. This indicates that while the two variables are correlated ($r = 0.42$), there may be more intricate dynamics at play, which cannot be illuminated by the data available here. Further analysis of these interactions can provide a much more nuanced illustration of community-level, interindustry dynamics.

As nanotechnology is not the first radical process discontinuity, it certainly will not be the last. And since new technological discontinuities will occur and emerge, it is important that we improve our understanding of this type of technology emergence. The current study builds on previous literature to provide insight into technology emergence through entrepreneurship and industry interaction, but several questions remain. Previous studies have examined interdependencies between industries by focusing on industry densities and entry (Wade, 1995; Lomi, 1995; Ruef, 2000; Mezias and Kuperman, 2000; Audia *et al.*, 2006) and employment (Sorensen, 2004). Following previous research, this study uses entry and density as proxies for

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industry interdependence. As such, further research using contrasting measures of interdependencies between industries is needed. For example, research examining the interdependence of industry mortality rates, mass, trade or technology development will prove insightful in our understanding of community dynamics. The findings of this study are also limited by unobserved heterogeneity. Collecting data on additional variables may help reduce the possibility of unobserved heterogeneity. Gathering more years of data may also reduce the correlation between covariates. Both would be useful in improving the modeling of these data.

Some may question the generalizability of research based on nanotechnology firms. While nanotechnology is a radical technological discontinuity with vast implications, it is not the first time that a technology has caused a foundational shift. Nonetheless, further research that explores other types of technological discontinuities will be useful. The development of other technologies that influence multiple industries such as steam engines, software, and clean energy provide fitting possibilities for future research.

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