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The Creation and Configuration of Infrastructure for Entrepreneurship in Emerging Domains of Activity

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Entrepreneurship is a perilous endeavor. Contextual changes, such as nascent technology emergence or new industry creation, can spawn entrepreneurial opportunities; however, these changes do not instantaneously create the resources and structures that new firms need to survive. This study examines the creation and configuration of the contextual infrastructure necessary for nascent technology entrepreneurship in new industries. Using the case of nanotechnology, I show how the elements of infrastructure emerge and configure through systemic coevolution. The data highlight how boundary crossing and obfuscation induces the configuration of separate elements into a cohesive infrastructure through heightened interaction and interdependence of organizations and institutions, both private and public.

Introduction

You can know the name of a bird in all the languages of the world, but when you're finished, you'll know absolutely nothing whatever about the bird . . . So let's look at the bird and see what it's doing—that's what counts. I learned very early the difference between knowing the name of something and knowing something. —Dr. Richard Feynman (Feynman & Leighton, 2011)

The role of context in entrepreneurship cannot be overstated. New ventures are embedded in their social and economic environment (Granovetter, 1985) and are imprinted with the context and conditions in which they are founded (Boeker, 1988, 1989; Saxenian, 1994; Stinchcombe, 1965). The environmental conditions prevalent while a new venture is developing influence its performance and survival (Aldrich & Ruef, 2006; Gnyawali & Fogel, 1994; Romanelli, 1989). In fact, entrepreneurial opportunities often arise from changes and shifts in environmental conditions (Sine & David, 2003). However, while

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contextual changes can stimulate entrepreneurial opportunities, they do not instantaneously create the resources and structures that new firms need to survive. As such, contextual changes give rise to environmental uncertainty. Emerging domains of activity based on nascent technologies tend to be especially uncertain, particularly before a dominant design has been determined (Anderson & Tushman, 1990). Moreover, when a technology is emerging, entrepreneurs may be entering a space that lacks a cohesive industrial structure or market infrastructure (Santos & Eisenhardt, 2009). Thus, new ventures based on emerging technologies in nascent industries must endure a *trifecta of burdens*: the firm's own liability of newness, the industry's lack of legitimacy and cohesive structure, and the technology's inherent uncertainty.

Despite these challenges, new firms survive, nascent technologies develop, and new industries emerge, often simultaneously. Although work has examined entrepreneurship in new industries and entrepreneurship using nascent technologies, comparatively little has brought the three emerging domains of activity together. Thus, we lack a theoretical framework to understand nascent technology entrepreneurship in new industries. Furthermore, much of the entrepreneurship research has focused on the individual or firm levels of analysis, while the context remains taken for granted (e.g., Dean, Shook, & Payne, 2007; Forbes & Kirsch, 2011). Existing work that has attended to context highlights three themes regarding the environment of theoretical importance for entrepreneurship: knowledge, support, and coevolution. These works tend to build on the supposition that the context of entrepreneurship is relatively established. However, we know relatively little about emerging domains of activity where a stable infrastructure may not exist. The trifecta of burdens for new emerging technology firms in nascent industries confirms a shortage of infrastructure or structures and materials on which firms rely. And although the importance of these theoretical constructs has been identified, we know little about how they coevolve or how the dynamic interactions of infrastructure elements influence the emergence of new firms. The development of infrastructure for entrepreneurship remains elusive. Thus, this study uses the existing literature as a foundation on which to build theory regarding the question: How does an infrastructure for nascent technology entrepreneurship in new industries form and configure?

The setting for this study is the emergence of entrepreneurship (new ventures) using nanotechnology. As a nascent market, nanotechnology has revolutionized multiple industries and opened a wide range of opportunities for entrepreneurship (Bozeman, Laredo, & Mangematin, 2007; Woolley, 2010). However, nanotechnology itself has no historical or industrial precedents (Rothaermel & Thursby, 2007), and infrastructure specific to nanotechnology entrepreneurship was not prevalent during its earliest years. Thus, nanotechnology provides a rich setting for the examination of infrastructure development. The study draws on over 11,000 pages of archival data regarding nanotechnology, firms, context, and infrastructure. Interviews from entrepreneurs and field experts provide additional insight. A robust and nuanced framework for understanding the creation and configuration of infrastructure for entrepreneurship emerges from the data.

The study detailed here cultivates three important contributions. First, by grounding the study in a foundation developed from multiple theoretical perspectives including organization evolution and the knowledge-spillover theory of entrepreneurship, a theoretically based framework emerges on which further studies can build. The framework highlights several opportunities for future investigation. Second, by examining not only how the existing infrastructure influences entrepreneurship, but also how entrepreneurs and organizations influence the emergence of infrastructure, we gain a more holistic understanding of the interaction between context, industry, and new firms. This study shows how entrepreneurship does not emerge as a result of new industries, technologies,

and infrastructure but is part of the emergence process. Third, the study illuminates how individually, elements of infrastructure play important roles in nascent technology entrepreneurship; however, these elements cannot stand alone. Each infrastructure element is necessary, but not sufficient to support an industry or technology. Without interaction, coevolution, and cross-development activities, the fabric of infrastructure is not formed. Furthermore, boundary crossing and obfuscation induces the configuration of the separate elements into a cohesive infrastructure for technology, industry, and firms enabling entrepreneurship to accelerate. In the space between new ventures and their institutional context, systemic coevolution and boundary obfuscation enable infrastructure creation and configuration.

The Emergence of New Firms, Technology, and Industry

Although the topics of nascent technology entrepreneurship and entrepreneurship in new industries have both received considerable study, the contextual factors that support the creation of new ventures in each setting have garnered less attention (Dean et al., 2007; Forbes & Kirsch, 2011; Woolley, 2011). Furthermore, literature rarely brings the three emerging domains of activity together, which has left a theoretical lacuna. The following section reviews the current understanding of contextual influences and new firm creation in the emerging domains of nascent technology and new industries, and discusses the role of relationships between new firms, technologies, and industries. Together, these literatures provide a framework for the study of entrepreneurship infrastructure.

Entrepreneurship and Nascent Technologies

Entrepreneurship and technology are uniquely intertwined. On the one hand, entrepreneurship can drive the creation and development of new technologies (Acs & Varga, 2005). In fact, new firms often generate technological variation (Wade, 1996), especially competence-destroying technologies (Tushman & Anderson, 1986). On the other hand, a nascent technology can create opportunities for new ventures (Shane, 2001). Indubitably, entrepreneurship and technology directly coevolve (Rosenkopf & Tushman, 1994).

The knowledge-spillover theory of entrepreneurship further elaborates the interdependence and coevolution of entrepreneurship and technology. This perspective posits that entrepreneurship is enabled by the creation of knowledge that leads to spillovers and new technologies (Acs, Braunerhjelm, Audretsch, & Carlsson, 2009).¹ Furthermore, entrepreneurial success requires knowledge acquisition, transfer, and learning (e.g., Audretsch & Keilbach, 2008). However, knowledge, especially tacit, is not easily conveyed between organizations. Physical or spatial proximity facilitates knowledge transfer (Freeman & Audia, 2006) and reduces costs of knowledge acquisition (Audretsch & Feldman, 1996; Jaffe, Trajtenberg, & Henderson, 1993). Subsequently, spatial proximity increases new firm foundations (e.g., Agarwal, Audretsch, & Sarkar, 2007; Carroll & Wade, 1991; Lomi, 1995; Sorenson & Audia, 2000) and industrial clustering (e.g., Audretsch & Feldman; Krugman, 1991; Marshall, 1920). For example, Saxenian (1994) found that structures for knowledge creation and transfer in Silicon Valley provided the support necessary for the emergence of the semiconductor industry. Technological proximity indicates the

1. Works that provide thorough overviews of knowledge spillover theory of entrepreneurship include Acs et al. (2009) and Agarwal et al. (2007, 2010).

localization of knowledge. Industries that are technologically proximate are more likely to share process knowledge and routines than those technologically distant, regardless of spatial distance (Orlando, 2004). Another study found that firms benefit from knowledge spillovers closest to their own physical location and technological space (Jaffe, 1986). In sum, spatial and technological proximity are important for knowledge spillovers and entrepreneurship.

Entrepreneurship and New Industries

Entrepreneurs transform markets through the process of “creative destruction,” during which new firms displace existing firms and create new industries (Schumpeter, 1942). New firms are often formed when entrepreneurs recognize problems in the environment and the incentives to solve them (Aldrich, 2008; Aldrich & Ruef, 2006). Multiple entrepreneurs attending to the same problem or institutional void can lead to the creation of new industries (Aldrich & Fiol, 1994). However, the effects of entrepreneurship are not limited to one industry (Mezias & Kuperman, 2000). In addition to being technologically or spatially close, industries can be structurally proximate through relationships. Structural relationships between industries provide means for knowledge transfer and reconfiguration (Audia, Freeman, & Reynolds, 2006). As such, entrepreneurship in one industry can create opportunities for new firm formation in related industries (Wade, 1995). Thus, knowledge spillovers and subsequent entrepreneurship increase not only with technological or spatial proximity but also with structural proximity.

New ventures in nascent industries also combat the inherent lack of legitimacy for both the firm and industry. Legitimacy is important to new firm survival (Singh, Tucker, & House, 1986). A new firm’s lack of legitimacy impairs its ability to obtain resources, which can undermine the growth of an industry as a whole (Aldrich & Ruef, 2006; Hannan & Freeman, 1989). If the legitimacy of a new firm increases, it is likely that legitimacy for its industry will also increase, and vice versa. As a result of increased industrial legitimacy, entrepreneurship in the industry increases, which fuels further industrial development and growth. An increase in legitimacy for a new industry can also improve that of related industries. Hence, entrepreneurship in a new industry can build legitimacy for both the industry itself and firms in related industries (Baum & Oliver, 1992; Mezias & Kuperman, 2000).

An increase in the number of ventures in an industry also means heightened competition. Since environmental resources are limited and firms require resources to survive, every setting has a carrying capacity of firms that it can support (Hannan & Freeman, 1989; Specht, 1993). In a new industry, density dependence dictates that firms are created until the carrying capacity is reached, at which point a firm’s ability to obtain resources decreases, firm mortality in the industry increases, and the number of foundings decreases (e.g., Carroll & Hannan, 1989; Hannan & Freeman; Haveman, 1994). Firms also compete for *access* to resources. A location may have a wealth of resources, but new ventures may not be able to access these resources without the relevant economic and social structures (Woolley & Rottner, 2008). In nascent markets, entrepreneurs attempt to strategically construct boundaries to overcome resource constraints and achieve dominance (Santos & Eisenhardt, 2009). Therefore, new venture creation is shaped not only by the level of resources but also by competition and structures that impede or facilitate access to resources (Begley, Tan, & Schoch, 2005; Saxenian, 1994).

The social systems perspective argues that industries emerge as “collective achievements” that include entrepreneurs and organizations that provide access to resources (Johnson & Van de Ven, 2002; Van de Ven, 1993; Van de Ven & Garud, 1989, 1993). In

addition to identifying the importance of legitimacy, competition, and industry interaction, the social systems perspective recognizes the roles of public resource endowments and proprietary firm functions. Together, these elements form an infrastructure of inter-related organizations and industries that supports innovation, entrepreneurship, and economic development (Venkataraman, 2004). While some elements of infrastructure correspond with influences on industry emergence discussed earlier, the social systems perspective highlights the role of actors that enable or support each element. For example, public resource endowments include scientific knowledge, financing, and competent labor (Van de Ven & Garud). Since these are typically developed by public organizations, resource endowments are considered public or common goods (Van de Ven & Garud). In congruence with the knowledge-spillover theory of entrepreneurship, the social systems perspective acknowledges the importance of knowledge; however, it also considers the support for knowledge creation, such as research funding and a skilled workforce, as equally significant. Scientific knowledge provides a foundation, but without further development by skilled workers, little technological invention and innovation can occur. Private proprietary functions of firms transform public resource endowments into commercial opportunities. Private proprietary functions include technological development, R&D, commercialization, manufacturing, marketing, and distribution (Van de Ven & Garud), which can develop products and, with adequate revenue, a viable firm (Mezias & Kuperman, 2000; Van de Ven). Together, entrepreneurship in new industries relies on public resource endowments and proprietary functions (Johnson & Van de Ven).

The social systems perspective also highlights the role of institutional arrangements that legitimate, regulate, and standardize (Van de Ven & Garud, 1989). Institutional arrangements include public organizations (e.g., government agencies), private entities (e.g., professional and industrial associations), and hybrid arrangements that combine public and private actors (e.g., standardization boards and interest groups). Institutional arrangements provide structure to emerging areas thus supporting new ventures, industries, and economies (North, 1990).

In summary, entrepreneurship can lead to the creation of new industries and influence new venture formation in related industries. However, new firms combat competition for customers and resources, along with an inherent lack of legitimacy for the firm and industry. The social systems perspective brings together elements that support entrepreneurship and new industry emergence into an integrated infrastructure. The next section examines work integrating entrepreneurship, new industries, and nascent technologies.

Nascent Technology Entrepreneurship in New Industries

Nascent technologies create opportunities for both new and incumbent ventures to form new industries. For example, a new industry can arise when the foundation of an existing industry or market is altered by a radical technological discontinuity, which is a rare revolutionary breakthrough in technology (Anderson & Tushman, 1990; Tushman & Anderson, 1986). Entrepreneurship after a radical technological discontinuity tends to occur first in upstream industries that subsequently provide opportunities for the development of downstream industries and facilitate the creation of the technology's supply chain (Woolley, 2010). Nascent technology firms founded while a dominant design is emerging are less likely to fail than firms that enter later (Suarez & Utterback, 1995). In turn, industry composition after the emergence of a dominant design favors the first-mover firms. Entrepreneurship in nascent technology domains also influences the emergence of new industries. For example, Giarratana (2004) found that product diversification of new ventures shaped the creation and development of the encryption software industry.

New industries based on nascent technologies require knowledge creation and acquisition (Murtha, Spencer, & Lenway, 2001). Incumbent firms shape industry evolution by investing in technology that enables knowledge spillovers and new entrepreneurial opportunities (Agarwal et al., 2007; Agarwal, Audretsch, & Sarkar, 2010; Saxenian, 1994). However, not all industries require the same level of knowledge spillovers. For instance, Kenney and Patton (2005) find that the biotechnology industry and its network are more dispersed than either the semiconductor or telecommunications equipment industries implying that the use of knowledge spillovers in these three high-technology industries differs.

Key Themes in the Literature

Separately, these streams of research identify several themes relevant in understanding the contextual factors that support entrepreneurship in new industries based on nascent technologies. The themes were identified as first-order constructs, which are listed in Table 1. Overarching second-order constructs emerge from the research reviewed here. For example, each stream of research discussed coevolution. In the entrepreneurship and nascent technology stream, work discussed how nascent technologies and entrepreneurship coevolve, creating opportunities for the development of each other. The entrepreneurship and new industries stream identified that entrepreneurship can catalyze the creation of new industries, upending incumbent firms that are unable to compete. In turn, new industries open opportunities for new venture formation. The last stream shows that entrepreneurship, nascent technologies, and new industries intersect in a web of interaction that shapes the development of one another. Similarly, each stream of research identifies the importance of knowledge and support structures.

The second-order constructs identified here indicate categories of activity found theoretically important for entrepreneurship in emerging domains. However, when firms,

Table 1

Analysis Framework

Stream	First-order themes	Second-order coding
Entrepreneurship and nascent technologies	Nascent technologies to create entrepreneurial opportunities	Coevolution
	Entrepreneurship to create and develop technology	Coevolution
	Knowledge spillovers and spatial proximity	Knowledge
	Knowledge spillovers and technological proximity	Knowledge
Entrepreneurship and new industries	Creative destruction	Coevolution
	Knowledge spillovers and structural proximity	Knowledge
	Competition dynamics	Support (-)
	Legitimacy and institutional arrangements	Support
	Social systems and infrastructure	Support
	Public resource endowments	Support
	Proprietary firm functions	Support
Entrepreneurship, nascent technologies, and new industries	Triad interaction	Coevolution
	Knowledge creation and spillovers	Knowledge
	Proximity and related industries	Support

technologies, or industries are emerging, these constructs may not exist. Furthermore, entrepreneurs in a new industry based on an emerging technology must endure a *trifecta of burdens*: their own liability of newness, the industry's lack of legitimacy and structure, and the technology's inherent uncertainty. Although important constructs have been identified, we know little about their temporal relationships and even less about how their dynamic interactions influence the emergence of new firms. Thus, this study uses the framework derived here to further examine the temporal dynamics involved in nascent technology entrepreneurship in new industries.

Methods

This study uses the grounded case study approach to examine the creation and configuration of infrastructure for entrepreneurship. The single case study method is well suited for this type of research question since it facilitates an in-depth analysis of a complex social phenomenon (Eisenhardt, 1989; Yin, 2008). This study uses the framework detailed above as its foundation by treating each construct as an embedded unit of analysis within the case (Yin). The data were analyzed for each construct separately and then relative to other constructs. The creation and the configuration of infrastructure are examined iteratively as relationships between the constructs develop (Eisenhardt).

Setting

The setting for this study is the emergence of nanotechnology entrepreneurship. Nanotechnology is most commonly defined as the development and use of products that are less than 100 nanometers (National Science and Technology Council, 2000).² A nanometer is one billionth of a meter, about 1/80,000 of the diameter of a human hair, or the width of about 3 to 10 atoms. While nanotechnology is smaller than technology at the micron level by a factor of 10, the physical properties of nanoscale molecules are different from those at a larger scale.

The recent emergence of nanotechnology offers an opportunity to observe a technology from its conception through commercialization (Rothaermel & Thursby, 2007), as well as the creation and configuration of infrastructure and entrepreneurship. Although nanotechnology was built on existing knowledge, it required new funding, supply chains, and institutions to reach commercialization (Rothaermel & Thursby). Similarly, firms using nanotechnology must, by definition, manipulate matter smaller than 100 nanometers. However, before 1981, equipment to see or move matter at this level did not exist (National Nanotechnology Initiative, 2006b; Smalley, 1999). Thus, the starting point for nanotechnology-related entrepreneurship is established as no earlier than 1981.

Data

This study uses longitudinal data from archival sources written between 1976 and 2010 and 40 semi-structured interviews that took place between 2005 and 2007.³ Using two different types of data allows for triangulation, which is the inclusion of two or more

2. For a detailed account of nanotechnology, see Berube (2006), or visit <http://www.nano.org>.

3. The year 1976 was used as a starting point for the archival data to include 5 years of pre-entrepreneurship activity in nanotechnology.

dissimilar research instruments that do not have the same methodological weaknesses and strengths (Jick, 1979). This enables the researcher to “zero-in” on the findings (Jick) and increases the validity of the results (Singleton & Straits, 2005).

Archival Data. Archival data collection started with documents from organizations, government agencies, industry associations, scientific communities, and technology developers to gain a range of perspectives. Documents include reports, technical papers, newsletters, media reports, websites, and press releases, which are summarized in Table 2. Organizations were selected from participant lists of nanotechnology-themed conferences in the United States held before 1999 (e.g., Foresight, NanoCon Northwest, Gordon Research, Nano Science and Technology Institute; see also, Garud, 2008). Government documents were collected from the United States, China, United Kingdom, Japan, Germany, and Canada, as these were the first countries to sponsor nanoscience research. The government documents were published between 1985 and 2010, and include research awards reports, funding program solicitations, and U.S. congressional testimony transcripts.

However, data from one source were often limited, leaving many questions unanswered (e.g., the specific actors involved in an event). Thus, additional data were collected from associations and groups, universities, media, market research firms, and other firms. Press releases document nanotechnology advancements and proprietary activity in firms including patents and product launches. Using such data helped reduce retrospective bias

Table 2

Archival Data Summary

Population	Data source	Dates of origin	Estimated pages
Government	National Science Foundation	1985–2010	2000
	National Nanotechnology Initiative	1999–2010	1100
	Department of Energy	1985–2010	400
	Interagency Working Group on Nanoscience & Engineering	1999	400
	Organisation for Economic Co-operation & Development	2006–2010	150
Associations, technical groups, and business groups	Foresight Institute	1986–2010	2000
	IEEE Nanotechnology Council	2000–2010	200
	International Association of Nanotechnology	2004–2006	400
	NanoBusiness Alliance	2001–2009	150
	Nano Science and Technology Institute	1998–2010	150
Universities	13 NNIN participants	2004–2010	250
Market research firms and consultants	Lux Research	2000–2010	100
	Gartner Research	2004–2005	50
	NanoMarkets	2006	50
	Woodrow Wilson Center	2005–2010	100
	Media	NanoTechWire	2005–2009
Nano Investor News		2002–2005	100
NanoVIP		2005	350
Small Times Media		2004–2010	300
Nanowerk		2006–2010	100
Nanotechweb.org		2005–2010	500
MIT Technology Review		2007–2010	100
Press releases and other	PR Newswire	1981–2010	1400
	Other (articles, reports, lectures)	1976–2010	1000
	Total		11250

from documents and interviews written or conducted later. Data were corroborated across multiple sources when possible to reduce single-source bias, gain “distance” from the phenomenon, and maintain objectivity (Strauss & Corbin, 1998, p. 44). Data collection continued until reaching the saturation point at which point additional data contributed only marginal insights (see Eisenhardt, 1989). In total, the data include more than 11,000 pages from more than 30 organizations.

A database of nanotechnology firms founded before 2006 was compiled from the data. Nanotechnology firms are single-business ventures founded to develop, produce, and sell nanotechnology products, with more than 50% of their activity (i.e., products, R&D, or revenue) at the nanoscale. This definition excludes service providers, captive producers, subsidiaries of existing firms, distributors, and custom engineering firms. The final database included 303 nanotechnology firms, which were verified against that of other researchers. We investigated discrepancies, but no additional firms were identified meeting the criteria. Demographic data and the dates of founding and death were recorded for each firm.

Interviews. Archival data were augmented with 40 semi-structured interviews of nanotechnology experts in the United States including firm founders, CEOs, and employees of nanotechnology firms, current and former government employees directly involved in nanotechnology policy, professors, and consultants in the field. Participants were identified using the aforementioned conference proceedings. Interviews were conducted between 2005 and 2007. Each started with a set of open-ended questions and progressed to free dialogue. Interviews lasted between 20 minutes and 3 hours and covered the topics of entrepreneurship and commercialization as well as the role of actors and institutions in the formation of the nanotechnology field. Each interview was documented and, when participants agreed, digitally recorded and transcribed.⁴

Analysis

Data were analyzed in recursive stages grounded by the theoretical framework derived from the literature (Glaser & Strauss, 1967). First, the data were coded for nanotechnology-related events and actions. Events consist of a particular time in which a distinguishable phenomenon occurs such as a trade show or ceremony (e.g., Anand & Watson, 2004; Lampel & Meyer, 2008; Oliver & Montgomery, 2008). The coding process led to the recording of more than 600 events. Each event was then coded using second-order constructs and then using first-order themes. For example, the National Science Foundation (NSF) awarding research and development funding to physicist Dr. Nano at Cornell University would be coded as support (specifically legitimacy, institutions, infrastructure, and public resources) and knowledge (knowledge creation and spillovers). Actors involved in the events or actions were coded for the organization type and actor position (if available). In the example above, the NSF would be coded as a government agency, Cornell would be coded as a university, and Dr. Nano would be coded as a university researcher. Additional coding for each event included the text of the original data source, the date of the event, the source, the author, and the name of the archival document.

Next, using a process method (Van de Ven & Poole, 2005), the data were examined for patterns, trends, and themes over time and in relation to other events. Tools for identifying such patterns include longitudinal tables, charts of events, and frequency of codings (Miles &

4. In total, 19 interviews were recorded and transcribed.

Huberman, 1994). These were further compared for additional patterns, trends, and themes to explicate their configuration. The resulting case was thus built using an iterative process of data analysis and theory reflection (Eisenhardt, 1989; Siggelkow, 2001; Yin, 2008).

Results

The process of infrastructure development for nanotechnology entrepreneurship was not a linear process broken into discrete sequential phases; it was messy. By using the framework of themes and constructs generated from the literature, key elements of infrastructure emerged from the data. The next section details these elements, specifically knowledge and public resources, proprietary resources, and institutionalization mechanisms. Each element is necessary but not sufficient for firm and industry formation. Likewise, no one actor controls or configures every element of infrastructure. The following section brings the components together to discuss the synchronicity of events and actors. The results show how boundary crossing and obfuscation induces the configuration of the separate elements into a cohesive infrastructure for technology, industry, and firms, thus enabling entrepreneurship to accelerate.

Building Knowledge and Public Resources

Nascent technology entrepreneurship in new industries requires the use of knowledge and other public resource endowments such as financing mechanisms and competent labor (Van de Ven, 1993). Initially, nanotechnology did not have a foundation of knowledge or endowments and existing firms, universities, and public organizations developed much of these elements. And although this foundation did not directly become new firms, it provided opportunities for entrepreneurship. This section first shows how knowledge and public resources specific to nanotechnology entrepreneurship were built. Then, the section examines how these cultivated entrepreneurial opportunities.

Knowledge and other public resources for nanotechnology were developed over the history of science, but notably manifested in the invention of the scanning tunneling microscope (STM) by Drs. Gerd Binnig and Heinrich Rohrer at IBM. The STM was the first instrument to enable scientists to observe, move, and modify a nanoscale sample in three dimensions (Woolley, 2010).⁵ The STM also enabled further development of nanotechnology. “It’s the most important new tool to come out of physics or biology in this century,” said Dr. Stuart Lindsay, Associate Professor of physics at Arizona State University (Pennisi, 1988). However, IBM did not seek to commercialize the STM, but it did continue research in the area.⁶ For example, at IBM, Drs. Binnig (STM inventor), Christoph Gerber, and Calvin Quate invented one of the next foundational scientific breakthroughs for nanotechnology: the atomic force microscope (AFM). The AFM improved upon the STM by enabling scientists to see nonconductive material samples at the nanoscale for the first time. As such, the STM and AFM “provide the ‘eyes’ and ‘fingers’ required for nanostructure measurement and manipulation” (National Science and Technology Council, 2000, p. 20). The STM and AFM are fundamental public resources that have enabled the creation of knowledge and countless discoveries.

5. Drs. Binnig and Rohrer were awarded the 1986 Nobel Prize in physics primarily for their nanotechnology-related inventions.

6. Communication with Dr. Gerber, 2009.

Patent data also show how knowledge and public resources developed. The earliest nanotechnology-related patents issued by the U.S. Patent and Trademark Office mainly addressed manufacturing methods and conceptual instrumentation that reached the nanoscale. These were invented in existing firms and organizations such as IBM, the U.S. Navy, Eastman Kodak, RCA, and Texas Instruments.⁷ Instead of occurring in industries directly related to the nascent technology such as measurement tools (Carroll, Bigelow, Seidel, & Tsai, 1996; Klepper & Simons, 2000), early nanotechnology inventions occurred in tangential industries out of necessity—the items did not exist but were deemed critical for product development. Additionally, the inventions were in industries upstream from the focal firms, that is, the industries of their suppliers. However, the inventions were not strategic R&D for firm diversification; the firms did not attempt to enter the industries of the inventions. The firms that finally transformed the inventions into commercial products became upstream suppliers to the incumbents. In fact, the inventing organizations were the very same organizations that would eventually buy the commercial innovations, thereby *creating a market and supply chain*. In essence, the organizations that produced some of the earliest knowledge and public resources became the market for other upstream firms that were able to transform these inventions into viable products. Existing organizations shaped the foundation of nanotechnology but did not concentrate on commercializing their breakthroughs. This was left to entrepreneurs.

As industrial and university researchers built knowledge and invented breakthrough nanotechnology, other components of public resources such as financing mechanisms and facilities did not immediately manifest. During the early years, the majority of researchers could not seek funding to support their work under the guise of nanotechnology since it was still considered empirically impossible and, thereby, not worth funding. Instead, researchers sought funding by framing their projects in terms of their home scientific disciplines, mainly physics, chemistry, and engineering. Since nanotechnology-specific funding did not exist, such research proposals targeted programs in the established fields, which required discipline-specific results. However, a further complication remained: nanotechnology requires the integration of knowledge across scientific disciplines (National Nanotechnology Initiative, 2006a). “Rapid advances in nanoscale science and engineering can only thrive in a collaborative environment where faculty and students from different disciplines discuss ideas, collaborate, and share their experiences” (Vogel & Campbell, 2002, p. 498). However, researchers in universities and firms found that they were constrained by a reliance on existing institutions that largely lacked interdisciplinary funding and encouraged discipline-specific advancements. In this way, existing institutions limited the development of knowledge and public resources for nanotechnology infrastructure.

To overcome obstacles, researchers established informal study groups, cross-discipline symposia (e.g., MIT’s Nanotechnology Study Group in 1985), specific courses (e.g., Dr. Eric Drexler’s at Stanford University in 1988 and Dr. Ari Requicha’s at University of Southern California in 1994), and dedicated research labs (e.g., at Rice University in 1993). In response to the growing demand for facilities, the NSF sponsored the creation of the National Nanotechnology Users Network (NNUN) in 1993. Five universities participated: Stanford University, Cornell University, Howard University, Pennsylvania State University, and University of California—Santa Barbara. Each university obtained expensive equipment necessary for nanotechnology research.

7. Three of the next breakthroughs in nanotechnology also occurred in existing firms in tangential fields: the creation of the nanoscale IBM logo in 1989, the invention of the atomic switch by Drs. Schweizer and Eigler at IBM in 1991, and the discovery of the nanotube by Dr. Iijima at NEC in 1991.

The NNUN facilitated the development of knowledge and public resources in several ways. First, access to the facilities was not discipline specific. Since most university departments could not afford to purchase or rent the expensive equipment needed for nanotechnology R&D, the NNUN expanded the capabilities of multiple departments at the same time. Consequently, the number of departments that could conduct nanotechnology R&D increased. A wide range of disciplines participated including physics, chemistry, engineering, electronics, biology, and medicine. In turn, researchers at NNUN facilities gained a broad range of expertise by crossing discipline boundaries. The NNUN also facilitated the education and development of cross-trained workers needed for nanotechnology jobs.

Second, the facilities were not restricted to member universities. In fact, researchers of other universities and firms were encouraged to use the facilities. As described by Joanna Evans (1999) of the Stanford Nanofabrication Facility:

The smorgasbord of equipment available at NNUN facilities is certainly a strong draw for prospective researchers. Although much of the equipment is available commercially, start-up companies and researchers with highly innovative projects often have difficulty competing for lab time in the marketplace.

This access policy increased the number and scope of organizations able to conduct nanotechnology research. Third, NNUN facilities provided a place for researchers to gather and share expertise. The colocation of heterogeneous users facilitated communication across disciplines and organizations, thus increasing probabilities for knowledge creation and transfer. Again, boundary crossing was essential to nanotechnology R&D. This colocation was invaluable for firms, especially start-ups that could not afford to employ multiple experts in different fields. In fact, it was not unusual for start-ups to seek advice from other NNUN facility users. In this sense, the NNUN lowered the barriers to entering the nanotechnology market. Between 1994 and 2000, users from 29 states, seven foreign countries, and more than 50 start-up firms accessed the facilities. Ultimately, the NNUN helped spawn dozens of new firms primarily through active professors and graduate students. For example, Nanofluidics Inc. was started by Cornell University Professor Craighead and his graduate student, Dr. Turner, in 2000.

Although the creation of nanotechnology knowledge and public resources was not entrepreneurship itself, it did spark creative destruction that formed new market opportunities (Schumpeter, 1942). The next section describes how some of these opportunities were transformed into entrepreneurial ventures.

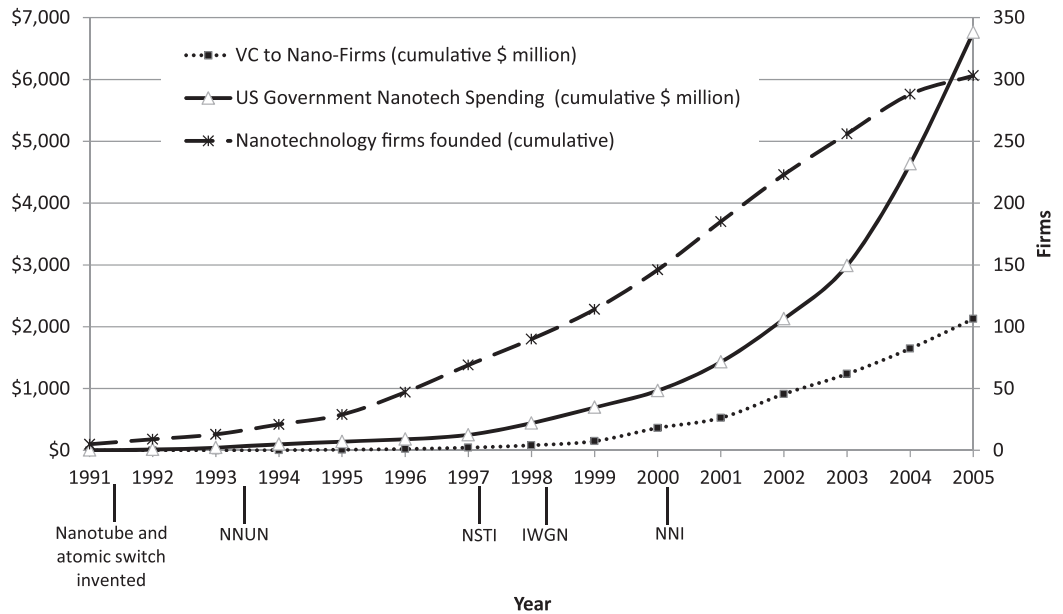
Entrepreneurial Opportunities and Proprietary Resources

Proprietary functions are a firm's ability to change knowledge and public resources into products and services for commercialization. In other words, the creation of knowledge and other endowments acts to build technological inventions, while proprietary functions enable the innovation needed to take these inventions to the market. For example, Binnig, Rohrer, and colleagues generated public resources with their invention of the STM and AFM. The transformation of these inventions into products in the microscopy market was a proprietary function.

Dr. Virgil Elings took on the challenge of commercializing the STM and AFM in 1987 when he formed a firm to license IBM's technology, Digital Instruments. This was the first firm started to specifically target nanotechnology applications, followed the next year by Park Scientific Instruments and JC Nability Lithography. However, the number of nanotechnology firms did not grow quickly. Figure 1 shows the number of

Figure 1

Nanotechnology Events, Funding, and Firm Foundings, 1991–2005



nanotechnology firms founded each year from 1991 through 2005. By the end of 1993, only 10 such firms existed in the United States, and fewer than 10 were founded each year through 1996.

Knowledge and public resources generated by university breakthroughs also provided fodder for the creation of new firms. Almost half of the first 13 nanotechnology firms were started by university professors including Nanoprobes Inc. and Molecular Imaging Corp. Additionally, of the nanotechnology firms founded before 1995, 35% were founded by university professors, and another 10% by university students. These firms cited the research of founders as one of their technological foundations. Thus, universities served as an important source of knowledge and public resources for early nanotechnology entrepreneurship.

Capital support for new firms came from a range of sources. While founders, their friends, and family funded the earliest nanotechnology firms, the U.S. government also provided considerable funding. In fact, about three quarters of nanotechnology firms started before 1997 had government support in terms of Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) grants, contracts, and NSF grants, mainly from the Department of Defense and Department of Energy. The government’s provision of funding mechanisms for proprietary nanotechnology R&D directly supported early entrepreneurship; without governmental support, many of these firms would not have been created.

Venture capital (VC) aids in the formation of new firms and the development of new technologies (Avnimelech & Teubal, 2006). Venture capitalists not only contribute financial resources, but also, they help build legitimacy for emerging fields (Aldrich & Ruef, 2006). Sixteen percent of the nanotechnology firms started before 1997 were supported by

VC; however, 85% of these investments took place after 2002. Venture capitalists invest in firms from which they can obtain high returns in a relatively short time period, which often requires demonstrated technology and products. Experts interviewed observed that nascent nanotechnology firms tended to not have products or revenues because they often had complicated technological issues to resolve that require considerable time. The CEO of an early nanotechnology firm summarized,

Well, no we don't have a product. What we have here is a technology platform that allows us to make a lot of different things that ultimately are probably useful for a wide variety of customers and markets. But, as a startup company and given that the use of nano-particles is fairly new, nobody really knows.

Therefore, investing in these firms is considered more risky and less appealing. Figure 1 shows U.S. VC and government nanotechnology funding provided annually from 1991 through 2005.⁸ VC to nano-related firms through 1997 totaled less than \$50 million and reached about \$350 million in 2000. U.S. VC funding for all firms totaled over \$150 billion in 2000; however, the percentage allocated to nano-related firms totaled less than *a quarter of 1%*. Overall, VC firms did not significantly fund nanotechnology firms until the year 2002. As shown in Figure 1, U.S. government funding to nanotechnology was consistently more than two times that furnished by VC through 2003, reaching three times in 2004. Even so, government officials are quick to admit that industrial spending on nanotechnology R&D consistently met or exceeded that of the government. Therefore, VC was a small fraction of the total funding for nanotechnology R&D. Furthermore, Lux Research reports that VC to nanotechnology firms started to decrease in 2007. Despite being commonly seen as a driver of industry creation, early entrepreneurship in nanotechnology was not greatly supported by VC.

Legitimacy and Institutional Mechanisms

Nanotechnology was not a legitimate activity upon invention. Initially, it was considered “purely theoretical.” However, it was not only a problem of newness. Conceptual and practical challenges plagued the advancement of nanotechnology from the beginning. For example, nanotechnology was impossible to see without specialized equipment and training. As one researcher stated: “Nanotechnology will create some interesting contractual problems: it's all very well telling someone to shave another couple of nanometres off a bearing, but how can you tell if they have done it?” These challenges suggest uncertainty and risk that deterred investment into nanotechnology firms. One analyst reported that investment into nanotechnology was deterred by “fear that the technology is being oversold and . . . uncertainty about potential environmental hazards.”

Institutions provide the regulative and normative function of infrastructure through legitimation, regulation, and standardization (Scott, 2008). Several contributors to the generation of nanotechnology knowledge, public resources, and proprietary functions and resources also acted to normalize and legitimate the technology as well. For example, government and private funding of nanotechnology R&D signaled support for continued

8. Venture capital figures were aggregated from several sources including Price Water House Coopers MoneyTree, Gartner Research, and Lux Research. These sources use a broader definition of nanotechnology and include subsidiaries, software, and firms with less than 50% nano-related activity. Thus, these data do not align completely with the nanotechnology firm database compiled for this study.

activity in the field and, in turn, helped establish legitimacy. Similarly, university researchers creating symposia, courses, and programs also increased the legitimacy of nanotechnology through their interest and activities.

Industrial, scientific, professional, and trade associations played multiple roles in the creation and configuration of the infrastructure. Work has shown that groups and associations are critical to field emergence (Greenwood, Suddaby, & Hinings, 2002). In particular, associations can facilitate (or inhibit) the development of learning, knowledge dissemination, and legitimacy for a nascent technology (Aldrich & Ruef, 2006; Sine, Haveman, & Tolbert, 2005). Similarly, new associations were important to the emergence of nanotechnology; however, this activity did not occur early in the infrastructure's emergence. For example, few nanotechnology-related associations appeared until the late 1990s. The Nano Science and Technology Institute (NSTI) was formed in 1997 with business development for nanotechnology firms and cross-industry education as its primary goals. The NSTI is the first evidence of a nanotechnology-specific professional or trade association. In 1998, the NSTI started the first international nanotechnology conference hosting business and technical presentations, early-stage firm presentations and reviews, expert panels, and exhibitors. The conference brought together entrepreneurs, researchers, and government officials. This conference was critical for establishing a platform of communication between research and commercialization, and between supply chain partners. In contrast to the NNUN, the NSTI conferences served to disseminate knowledge about technology closest to commercialization. Other associations with activities dedicated to supporting nanotechnology market development included the European Society for Precision Engineering and Nanotechnology (started in 1997) and the European Consortium on NanoMaterials (started in 1996). In 1998, the Semiconductor Manufacturing and Technology Institute and the Semiconductor Research Corporation started developing research activities to bridge the capabilities of nanotechnology with the semiconductor industry. In this way, the professional, industrial, and technology organizations provided access to information that developed nanotechnology product supply chains but were not the primary movers in institutional development.

Government institutions facilitated legitimacy building through the creation of nanotechnology-specific councils, workshops, and programs. In 1995, the Program Director of the NSF, Dr. Mihail Roco, organized a group of researchers and experts from 12 government agencies, universities, and national labs to discuss long-term plans for nanotechnology in the United States (Roco, 2006). As a result, the NSF established a \$10 million program, "Partnership in Nanotechnology: Functional Nanostructures," in 1997 to fund 24 small interdisciplinary research projects on nanoscale materials. In 1998, President Clinton formally designated the group as the Interagency Working Group on Nanoscience, Engineering, and Technology (IWGN), tasked with planning the advancement of nanoscience in the United States (National Science and Technology Council, 1999). By 1999, the IWGN included more than 50 participants from a diverse spectrum of organizations including universities (e.g., California Institute of Technology, Cornell University, Rice University, University of California—Los Angeles), national labs and research projects (e.g., National Aeronautics and Space Administration, Jet Propulsion Laboratory, the Human Genome Project), government agencies (e.g., Department of Energy, Department of Commerce), and firms (e.g., Hewlett Packard, IBM, Ford, Exxon, Merck, Dow, Monsanto, Eastman Kodak) (Roco, Williams, & Alivisatos, 1999). The IWGN gathered nanotechnology experts in one forum that facilitated knowledge sharing across research labs and industry. Here, the members were expected to cross boundaries. Although the IWGN did not have funding capabilities, the group produced reports in favor of government funding to both university and industrial researchers, including those at

nascent firms. Thus, the IWGN heightened the awareness and value of nanotechnology research in both academia and industry, further legitimating entrepreneurship in the field. As the NNUN constructed some of the first multidisciplinary, cross-industry research facilities and the NSTI generated one of the first commercially oriented fora, the IWGN established a forum to plan for the strategic use of resources for the coordinated advancement of nanotechnology. Each of these created value by using boundary obfuscation to enable knowledge creation and transfer.

One immediate outcome of the IWGN was the proposal of a nationwide nanotechnology research funding program. Additional support for the proposal was contributed through the congressional testimony of executives (e.g., Xerox, Exxon, and Motorola) and university researchers (e.g., Dr. Richard Smalley, NSF Director Dr. Neal Lane). Subsequently, on January 21, 2000 at the California Institute of Technology, President Clinton announced the National Nanotechnology Initiative (NNI) with a \$465 million budget.⁹ Nanotechnology had grown from what was considered an impossible dream into the focus of one of the largest federal science initiatives in history. Recalling the passage of the NNI, physicist Dr. James Heath remarked, “A couple of years earlier, I couldn’t even convince people that nano was a real field” (Lok, 2010).¹⁰ Similar to the IWGN, this new institution was created by influential actors involved in creating knowledge and public resources, proprietary resources, and existing institutions.

The NNI’s activities crossed into each of the infrastructure elements identified by this study. First, the NNI directly funded the development of knowledge and public resources in universities, national labs, and firms conducting nanotechnology research. For example, in fiscal year 2001, the NNI provided more than \$100 million for research to individual investigators and small groups, particularly new firms. Second, the NNI supported the creation of proprietary resources in new firms by issuing innovation grants through several government agencies. For example, the NSF started new solicitations for nanotechnology SBIR grants immediately after the agency was allocated funding from the NNI. Third, institutions obtained support to conduct standards and regulations-related work (Rao, 1994; Tasse, 2000). For example, the Department of Justice and the Environmental Protection Agency (EPA) were allocated NNI funds to study potential privacy issues and environmental impact, respectively. Finally, the market grew as both government agencies and firms sought nanotechnology products, increasing demand and further building the supply chain. Thus, the NNI supported each infrastructure component.

The implications of the NNI were far-reaching and immediate. For one, it acted as a signal of support from the government, thus facilitating legitimacy building. Several experts in the field specifically stated that the passage of the NNI was one of the most important events in the development of nanotechnology. For example, specialists in the field observed:

The success of the field is largely due to the early adoption of the National Nanotechnology Initiative by the U.S. government to fund nanotechnology research, which represented the largest government initiative in science since the “Space Race” in the 1960s. (Foster, Woolley, & Kawada, 2006)

9. This location is significant to nanotechnology since Dr. Richard Feynman, physicist and Nobel laureate, gave a talk at the 1959 annual meeting of the American Physical Society held at Caltech entitled, “There’s Plenty of Room at the Bottom” (Feynman, 1959). This is one of the earliest references supporting the possibility of molecular (nanoscale) manipulation and is regarded by many experts in the field as the launch of nanotechnology.

10. Dr. Heath was a student of Dr. Smalley at Rice University during the discovery of the buckyball—one of the first nanoscale particles.

When the first year of the NNI appeared successful, President Clinton requested a \$225 million (83%) increase for the following year. The CEO of a nanotechnology firm founded in 1997 said that before the NNI, his company was “not cool,” but “overnight, the NNI made nano [legitimate].” As we have seen, several factors contributed to the building of legitimacy for nanotechnology. The creation of the NNI acted as the culminating decisive event.

Systemic Coevolution

Participants in infrastructure creation and configuration such as government agencies, universities, national laboratories, incumbent firms, and new firms did not have single roles, nor did they attempt to remain sovereign. Similarly, the elements of infrastructure supporting nanotechnology entrepreneurship were not created in isolation; rather they required the development of each other. For instance, proprietary resources could not develop without knowledge and public resources. Coevolution is not dyadic between firms and technology or institutions. Coevolution is systemic—integrating technology, existing organizations, new firms, universities, government agencies, other institutions, and society at large (see, Baum & Singh, 1994; Nelson, 1994). The following section develops the nanotechnology case to explicate the role of systemic coevolution in entrepreneurship infrastructure configuration.

Boundary Obfuscation. Institutions and organizations play a variety of roles in society; however, literature often prescribes specific roles reflecting superficial norms. For example, universities are often prescribed the role of knowledge creators. This is a limited perspective. Not only do institutions and organizations act outside of their prescribed roles, but also, it is when boundaries are crossed that new arrangements are tested and developed. In the case of nanotechnology, infrastructure configured when boundaries were deliberately obscured. University–firm relations prominently exemplified the interlacing of knowledge, public resources, and proprietary resources. In addition to being involved in research that generated public resources, universities supported proprietary activities through collaborations with firms, user facilities, and technology transfer offices. For example, universities participating in the NNUN opened their typically restricted facilities to firms. This supported entrepreneurship and industry emergence by providing new and incumbent firms access to expensive equipment at a much lower price than other facilities—access that they may not have otherwise been able to afford. However, some argue that these universities became profit driven, seeking to maximize facility rental fees. Professors complained that, in some cases, the NNUN and similar emulating facilities shifted the priorities of the universities away from academic excellence. Nevertheless, external access was a condition of their NSF funding, which in turn became critical to industry–academia knowledge spillovers and commercial development of nanotechnology. As such, the NNUN exemplifies the boundary crossing and obfuscation necessary for infrastructure configuration.

Similar examples of boundary obfuscation include the commercialization of university-sponsored research through technology transfer offices and firm sponsorship of basic science research. As discussed, almost half of the earliest nanotechnology entrepreneurs were university professors attempting to commercialize their own research. Universities directly supported the research that led to new firm creation. Without public resources such as scientific knowledge, these early firms could not have been founded. As more academic spin-offs were founded, demand for research facilities, such as the NNUN, increased. At the risk of losing important researchers, universities adapted their policies to accommodate more flexible leave arrangements for entrepreneurial professors. Other

universities established explicit research relationships with firms to enable the cohabitation of key scientists. Thus, universities supported the creation of proprietary functions, while firms supported knowledge and public resource creation.

Boundaries also blurred when government regulatory agencies supported fundamental research, such as the EPA's funding of research on the environmental impact of nanotechnology. The IWGN instigated foundational support for research across disciplines, even though the agency was designated as a planning and advising body for the White House. Similarly, scientific associations such as the Institute of Electrical and Electronics Engineers (IEEE) and the American Physical Society sponsored nanotechnology research. Thus, while these organizations mainly provided institutional support, they also sponsored the development of public resources and knowledge.

The lines delineating public institutions and private firms often blurred. One example occurred when the U.S. government supported nanotechnology commercialization in the form of SBIR grants. Here, the distinction between government-sponsored public resources and private proprietary intellectual property blurred. Conversely, new and existing firms in the field also supported the creation of institutional mechanisms. For example, executives from not only incumbent firms, but also new firms such as Nanogen, Polychip Inc., and Biometric Imaging, Inc., participated in the IWGN. Many of the executives were also members of scientific and industrial associations, working to advance nanotechnology across industries. The overlap of institutional mechanisms and proprietary resources provided associative legitimacy for nascent firms and generated entrepreneurial opportunities. The overlap also facilitated the development of proprietary functions in new firms and their supply chains.

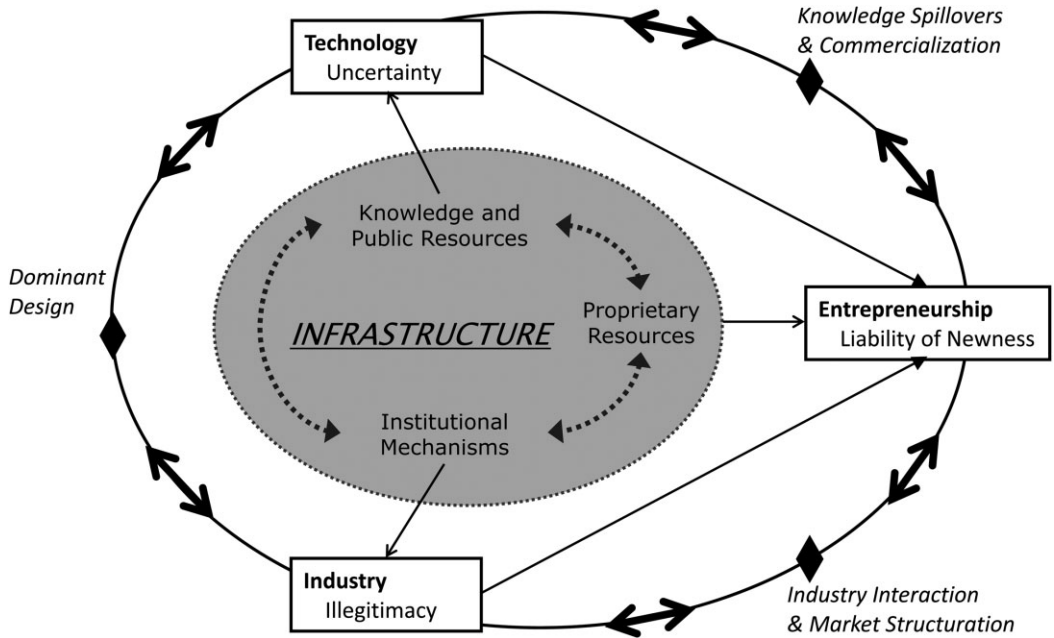
Boundary obfuscation defied the role of spatial proximity for developing entrepreneurship. Although the collocation of researchers in facilities such as the NNUN supported knowledge spillovers, spatial proximity between firms was not a strong driver of nanotechnology entrepreneurship. The first nanotechnology firms were geographically dispersed, such that the 68 firms started before 1998 were diffused across the 26 states. The only state with more than five nanotechnology firms was California; however, only half were located within 10 miles of one another. Firms founded before 1995 tended to be colocated with universities if started by professors or recent students. However, this trend did not continue, and the firms founded between 1995 and 1998 spread geographically, from 11 states to 26.

Technological and structural proximity interacted to influence nanotechnology entrepreneurship and infrastructure creation. Here, incumbent firms often created early inventions, but did not commercialize them. Instead, entrepreneurs founded upstream firms to realize the needs of the incumbent firms and fill demand for these nascent innovations (Woolley, 2010). Thus, nanotechnology entrepreneurship developed in part due to technological and structural proximity to the incumbent firms and universities that produced early knowledge and public resources. The firms founded before 1999 covered nine different industries, most notably instrumentation and materials. These firms created products used for R&D in semiconductors, energy, and basic sciences. Proximity was not industry specific as the creation of knowledge, public resources, and new firms in one industry formed opportunities for entrepreneurship in other industries. The importance of proximity was not due to space but due to knowledge.

Infrastructure Configuration. The core elements of infrastructure are depicted in the middle of Figure 2, inside an oval with a permeable border. No borders separate the elements, only shaded space to depict the boundary crossing and obfuscation necessary for infrastructure configuration. As described, nascent technology firms in new industries

Figure 2

Infrastructure for Nascent Technology Entrepreneurship in New Industries and the Trifecta of Burdens



endure a trifecta of burdens: the firm’s own liability of newness, the industry’s lack of legitimacy and cohesive structure, and the technology’s inherent uncertainty. Figure 2 depicts each of the three emerging domains of activity—technology, industry, and entrepreneurship—in boxes with their respective main burdens. This study shows how knowledge, public resources, institutional mechanisms, and proprietary resources are used to overcome these burdens. In Figure 2, each burden is connected to the infrastructure element essential for overcoming it. For example, knowledge and public resources enable the clarification of the uncertainty inherent in nascent technologies. Likewise, the lack of legitimacy of a new industry is combatted using institutionalization mechanisms (Aldrich & Ruef, 2006). In addition to knowledge, public resources, and institutional mechanisms, new ventures procure proprietary resources to overcome their own liability of newness. Nascent technology entrepreneurship in new industries must overcome each of these burdens, and thus require each element. However, the data here show how the elements are not independent. The elements interact and configure during systemic coevolution to become a cohesive infrastructure. Early firms lacking such infrastructure struggled. Entrepreneurs responded by working across boundaries to create infrastructure necessary for their own success and that of their customers and suppliers.

Knowledge, public resources, institutional mechanisms, and proprietary resources comprise the four fundamental components of infrastructure for nascent technology entrepreneurship in new industries. Each component is interdependent with the others. The configuration of infrastructure not only supports technological and industry emergence but enables further entrepreneurship. For example, nanotechnology entrepreneurship did not accelerate until after the three elements were developed: public resources and

fundamental scientific knowledge on the properties of nano-sized material, institutional mechanisms that legitimated the field, and proprietary resources supporting new firms. Figure 1 shows that while the number of nanotechnology firms increased over time, the rate of foundings accelerated during 2000 and 2001 while the NNI was enacted. The case findings suggest that as infrastructure is developed, nascent technology entrepreneurship increases. Additionally, when infrastructure configures (e.g., as demonstrated by the NNI), the trifecta of burdens is reduced, and entrepreneurship accelerates.

The model implies that as an infrastructure is created and configured, other activities occur, which are depicted on the outside of Figure 2. For example, as the burdens of technological uncertainty and industry illegitimacy are reduced, a dominant technological design emerges. Similarly, knowledge spillovers facilitate technology development and entrepreneurship based on that technology. Commercialization of the technology further helps to reduce the uncertainty of the technology and the illegitimacy of related entrepreneurship. Likewise, an increase of legitimacy for a new industry and an increase in entrepreneurship support industry interaction and market structuration, and vice versa.

Significantly, however, new nanotechnology ventures did not emerge as a result of infrastructure configuration. Entrepreneurs were part of the infrastructure itself from the very beginning. These firms commercialized foundational technology on which countless further nanotechnology inventions and innovations were based. For example, Digital Instruments, Park Scientific, and JC Naby Lithography were vital to commercializing the otherwise protected instrumentation that made nanotechnology possible. Early entrepreneurship in nanotechnology did not occur after a wealth of resource munificence accumulated. Instead, the entrepreneurs worked with what was available and helped create and configure infrastructure for future entrepreneurs. Nascent technology entrepreneurship in new industries accelerated when these early entrepreneurs, universities, government agencies, and other foundational stakeholders developed a holistic infrastructure through systemic coevolution.

Discussion and Conclusion

This paper contributes to our understanding of entrepreneurship by further explicating the contextual resources and structures that facilitate and constrain entrepreneurial action. The study started by examining the creation of infrastructure; however, the data reveal that although actors helped build different and often multiple elements of infrastructure, their interaction is critical for configuration. Each of the many people, organizations, and institutions involved in creating nanotechnology infrastructure were highly interdependent to the extent that without their interaction, an infrastructure could not have been built. Thus, it is not the amount of resources or the efficacy of resource mobilization that leads to infrastructure. The value of infrastructure is more than a sum of its parts, extending beyond resource munificence (Baum & Singh, 1994; Van de Ven, 1993) and institutional support (Barnett & Carroll, 1993).

Infrastructure for entrepreneurship configures because of interactions, in the space between the actors and elements where boundaries blur. Santos and Eisenhardt (2005, 2009) emphasize how new firms construct organizational boundaries in their attempts to deal with external interactions. In contrast, the study presented here draws attention to the importance of boundary crossing and obfuscating. Here, we see that boundary crossing enabled actors to participate in the construction of infrastructure that was considered outside of their traditional domain. Boundary obfuscation enabled actors to adapt and

realign as the environment changed.¹¹ Although boundary construction is important, perhaps we have overlooked the value of challenging and changing boundaries. Similarly, there may be a point at which boundary obfuscation and crossing changes from a benefit to a burden.

Practical implications of this study include a contribution to understanding how entrepreneurs take context into account when making market entry decisions. Previous research has focused on opportunity creation and recognition, while assuming that once an entrepreneur finds the opportunity, the context will be largely supportive. However, as seen here, an infrastructure for entrepreneurship may not be ready to support such activity in an emerging domain of activity. The ways that entrepreneurs evaluate the different elements of infrastructure for readiness has not been well studied. Evaluating the level of infrastructure in an area may prove a fruitful strategy for those entrepreneurs seeking to exploit or create an opportunity. In nascent markets where infrastructure is lacking, entrepreneurs can wait for infrastructure to be established or be part of its creation. Given the importance of both the context in which an entrepreneur starts a firm and the role that the firm plays in changing its context, an entrepreneur's evaluation of firm-infrastructure alignment or fit may influence decision making about entrepreneurship. Further research in both of these areas is encouraged.

Multiple actors including universities, existing incumbent firms, entrepreneurs, venture capitalists, policy makers, and social movements contribute to infrastructure. However, their degree of involvement varies as different needs and concerns are addressed, institutions enter or are created, and new challenges arise. The roles of actors change over time and are contingent on the actions of other actors in the field. The results discussed here step away from a nodal or actor-centric view of organizational processes toward a more systemic treatment of change. The study underscores the need for further analysis of how roles change during systemic coevolution.

Practical implications span each of the stakeholders in an emerging domain of activity. For incumbents, the study indicates opportunities to influence other industries and fields by creating complementary and symbiotic technologies. For universities, the study suggests that their relationship to incumbents is one of balancing rather than competing. Policy makers interested in developing a nascent technology can better determine the areas that lack support by evaluating the interactions of infrastructure elements. For example, to support entrepreneurship in a nascent technology domain, government agencies may want to consider how to strengthen systemic coevolution for infrastructure development.

As with any study, there are limitations and opportunities. As an individual case study, the results are not intended as generalizable across all cases. However, the case of nanotechnology entrepreneurship provides insight into other emerging industries and nascent technologies such as clean technology and genomics. As nascent technologies continue to change the world we live in, further examples will inevitably emerge. Although the study examines nanotechnology during its formation, this condition may also be a limitation. The analysis of firm data is constrained to the dynamics existing within the first decades of firms' lives. This limitation, however, is mitigated by the length of time that nanotechnology has been developing: entering its sixth decade. Nevertheless, a longer history may show a more complex process of infrastructure development. As we seek to broaden our understanding of organizations in their natural habitat, it has become clear that we must continue to improve our knowledge of the context in which organizations emerge.

11. The author thanks an anonymous reviewer for this suggestion.

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