The Space Between: Building the Infrastructure for Entrepreneurship in Nascent Markets

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Abstract

This study examines the creation and configuration of infrastructure for entrepreneurship. Using the case of nanotechnology's emergence, I show how the three elements of infrastructure, public resource endowments, institutional arrangements, and proprietary functions, are generated by a common set of actors, simultaneously, leading to boundary obfuscation and competition. Entrepreneurs did not wait until a critical mass of infrastructure accumulated, but started firms despite the lack of infrastructure. The earliest entrepreneurs endured a trifecta of burdens: their liability of newness, nascent market uncertainty, and ambiguity in the emergence of the technology itself. In exchange, early entrepreneurs were part of the infrastructure creation and configuration process. Additionally, I find that infrastructure is not measured by the amount of resources within an element or the efficacy. Infrastructure configures *because* of interactions between elements, in the space between the actors and elements where boundaries blur.

INTRODUCTION

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 (Stinchcombe, 1965; Saxenian, 1994; Boeker, 1988, 1989). As such, the conditions prevalent while a new venture is developing influence its performance and survival (Aldrich and Ruef, 2006; Gnyawali and Fogel, 1994; Romanelli, 1989; Granovetter, 1985; Brittian and Freeman, 1980).

Thus far, the study of the context of entrepreneurship has focused on that which catalyzes entrepreneurial opportunity creation and recognition such as radical shifts in a foundational technology (Tushman and Anderson, 1986), ideology (Haveman and Rao, 1997; Rao, 2004; Hiatt et al., 2009), regulations (Russo, 2001), or market fundamentals (Stinchcombe, 1965; Anderson and Tushman, 1990). These transformative changes in the environment take place over long periods. And while environmental changes can generate entrepreneurial opportunities, they do not instantaneously create the resources and structures that new firms need to survive. The new ventures that arise during or in response to environmental changes must navigate existing and developing structures and the ambiguous and changing social, technological, and economic environment to obtain resources, customers, and legitimacy. Thus, the development of an infrastructure to support entrepreneurship influences not only new firms, but also the development of the environment itself. However, the environment and infrastructure supporting entrepreneurship remains taken for granted in research (Forbes and Kirsch, 2011; Chandler and Lyon, 2001; Davidsson and Wiklund, 2001).

Van de Ven and Garud (1989) created a framework for industry emergence and later applied it to the emergence of cochlear implant technology and its subsequent industry formation

(Van de Ven and Garud, 1993). In their framework, the authors proposed that social systems provide infrastructure vital to industry emergence. This infrastructure consist of three main functions: technical instrumental functions, resource procurement functions, and institutional legitimation and governance. Van de Ven (1993) elaborated this framework by focusing on those factors specifically necessary to entrepreneurship: *public resource endowments, institutional arrangements*, and *proprietary functions*.

Studies exploring the context of entrepreneurship have tended to focus on how one component of an element of infrastructure influences the decision to start a firm (Tolbert et al., 2011) such as social networks (e.g. Aldrich and Ruef, 2006), social movements (e.g. Hiatt et al., 2009), government activities (e.g. Mok, 2005; Minniti, 2008), and competitive forces (e.g. Hannan and Freeman, 1977, 1989). Other studies have focused on how external elements influence new firm growth such as the availability of venture capital (e.g. Davila, Foster, and Gupta, 2003; Busenitz et al., 2004) and bank funding (e.g. de Bettignies and Brander, 2007). These studies provide exceptional insights into the actors and institutions necessary for entrepreneurship occur and succeed. However, little work has examined the development of the elements themselves or the configuration of these elements into a cohesive infrastructure. This study develops our understanding further by using a macro-lens to examine the interactions that shape infrastructure creation and configuration over time. Specifically, this study asks the question: How does an infrastructure for entrepreneurship form and configure?

To examine the creation and configuration of infrastructure for entrepreneurship, this study focuses on that which develops after a transformative change in technology. I analyze the emergence of infrastructure for entrepreneurship in nanotechnology across four decades, from its earliest conception through the emergence of new nanotechnology firms in multiple industries.

As a nascent market, the development of nanotechnology provides an unusually rich setting in which to examine the development of infrastructure for entrepreneurship. Nanotechnology has revolutionized multiple markets and opened a wide range of opportunities for entrepreneurship (Bozeman et al., 2007; Woolley, 2010). However, nanotechnology itself is emerging with no historical or industrial precedents (Rothaermel and Thursby, 2007). As such, an infrastructure specific to nanotechnology entrepreneurship was not prevalent during its earliest years. Scientific and technological breakthroughs in nanotechnology started in the late 1970's and early 1980's with the advent of the scanning tunneling microscope (STM) and atomic force microscope (AFM) (Rothaermel and Thursby, 2007). This study starts here, with data on the development of the STM and AFM from archival and interview data. In total, over 11,000 pages of archival data regarding the development of new nanotechnology firms and their context were analyzed. Interviews from 22 nanotechnology entrepreneurs and 18 additional nanotechnology experts provide insight into how the infrastructure elements were developed and shaped. A rich, nuanced framework for understanding the creation and configuration of infrastructure for entrepreneurship emerges from the data.

This study contributes to existing literature by showing that although infrastructure supports entrepreneurship, it is not required. Entrepreneurship does not wait until a critical mass of infrastructure is configured, but instead is part of the configuration process. Similarly, each element of infrastructure is necessary, but not sufficient to support substantial market creation. In fact, infrastructure for entrepreneurship comes together in the space between invention and commercialization, between the individual elements, entrepreneurs and their institutional context.

The paper proceeds as follows. The next section reviews literature regarding entrepreneurship and its infrastructure. Then, I describe the data and methods used to analyze the case of nanotechnology entrepreneurship. The results section details the development of an infrastructure for nanotechnology entrepreneurship, focusing on influences of the interactions. The final section discusses implications for theory, entrepreneurs, and policymakers.

INFRASTRUCTURE AND ENTREPRENEURSHIP

Entrepreneurship is a perilous endeavor as new ventures face the liability of newness that includes a lack of legitimacy, relationships, customer base, or internal routines and norms (Stinchcombe, 1965). Entrepreneurs in nascent markets face heightened difficulties compared to those faced in established settings due in part to a lack of cognitive and sociopolitical legitimacy for the market (Aldrich and Fiol, 1994). An example of a nascent market is that which arises after a radical technological discontinuity, or rare revolutionary breakthrough in technology, that alters the foundation of a market (Tushman and Anderson, 1986; Dewar and Dutton, 1986; Anderson and Tushman, 1990). A radical technological discontinuity can open opportunities for entrepreneurs to enter a market by founding organizations and exploiting innovations (Schumpeter, 1934; Aldrich and Fiol, 1994; Aldrich and Ruef, 2006). However, entrepreneurs who enter after radical technological discontinuities must endure a trifecta of burdens: their own liability of newness, the uncertainty inherent in the nascent market, and the ambiguity of emerging technology itself.

Despite the challenges, some entrepreneurs survive in nascent markets. Especially important to new ventures is the level of environmental munificence (Gnyawali and Fogel, 1994) as this represents the availability of resources in the ventures' environment (Pfeffer and Salancik, 1978; Specht, 1993; Begley et al., 2005). The level of environmental munificence available for new ventures must be evaluated in light of other contextual elements. For example, Stearns and colleagues (1995) argued that urban areas provide a higher level and wider variety of resources than rural areas and, thus, will have higher chance of new firm survival. However, they found that urban areas actually have a lower level of survival for new firms, potentially due to the higher competition for resources in urban areas. Similarly, while a location may have a wealth of resources, new ventures may not be able to access these resources without economic and social structures to facilitate access. Woolley and Rottner (2008) found that states with innovation initiatives have higher rates of related entrepreneurship due to the infrastructure that these policies provide to support entrepreneurial activity. Van de Ven (1993) identified three key elements of environmental munificence necessary to support entrepreneurship: public resource endowments, institutional arrangements, and proprietary functions. Together, these components create a "tangible infrastructure" that improves a regions innovation, entrepreneurship, and economic development (Venkataraman, 2004).

Public resource endowments are "basic resources necessary to support proprietary instrumental activities" (Van de Ven and Garud, 1989: 207). These endowments consist of three components: 1) basic scientific or technological knowledge, 2) financing mechanisms, and 3) a pool of competent labor (Van de Ven and Garud, 1989). Basic scientific knowledge provides the foundation for technological invention and innovation (Schumpeter, 1934). Since these are typically developed by public organizations, resource endowments are considered public or common goods (Van de Ven and Garud, 1989: 208). However, public resource endowments require considerable capital from funding mechanisms to support the people and equipment involved in its creation and development.

Institutional arrangements are organizations or structures that legitimate, regulate, and standardize a social system (Van de Ven and Garud, 1989). Since legitimacy is critical for the development of new organizations and populations (e.g. Suchman, 1995; Singh et al., 1986; Jepperson, 1991; Aldrich and Fiol, 1994), institutional arrangements that build legitimacy of a technology or ideology after transformative changes can support new ventures, new industries, and economies (North, 1990). To do so, the functions of institutional arrangements include "1) establishing governance structures and procedures for the overall industry, and 2) legitimizing and supporting the industry's domain in relation to other industrial, social, and political systems" (Van de Ven and Garud, 1989: 209-210). Institutional arrangements include standardization boards, professional associations, interest groups, and government agencies (Aldrich and Fiol, 1994). Specifically, standardization boards not only determine technology specific guidelines that facilitate product and supply chain development, but also they provide venues for knowledge sharing and legitimation activities (Tassey, 2000). Similarly, government or industry regulations, such as patent protection or manufacturing certification, can provide opportunities and help new ventures to legitimate a nascent technology (Aldrich and Ruef, 2006; Rao, 1994).

Proprietary functions are the transformation of basic knowledge from the public domain into proprietary knowledge (Van de Ven, 1993). These functions include technological development, R&D, commercialization, manufacturing, marketing, distribution, innovation network/resource channel activities, and the appropriation of common goods such as science, financing, and labor (Van de Ven and Garud, 1989). Proprietary functions create a flow of resources which enable additional firm activities, product production, and market growth. These proprietary functions can develop into products and, with adequate revenues, a viable firm (Van de Ven, 1993). In essence, proprietary functions are the activities that take place enabling basic knowledge to become a commercial product.

Work on the emergence of industries has focused the roles of social movements, institutions, and field configuring events as microcosms of nascent technologies, industries, and markets (Meyer et al. 2005). For example, work finds that conferences, tournaments, and competitions shape a nascent industries and fields (Garud 2008, Oliver and Montgomery 2008, Meyer et al. 2005; Anand and Watson 2004, Anand and Jones 2008, Glynn 2008, Rao 1994). Although these studies identify important institutions and events we know little about the temporal relationships among these influences and even less about how the dynamic interactions among other factors that influence the emergence of industries (McInerney 2008, Anand and Jones 2008).

As is evident in the discussion above, several actors have been identified as correlated to elements of infrastructure. Particularly, public resource endowments are tied to universities, governments, banking, and venture capital; institutional arrangements are tied to governments, professional groups, and institutional entrepreneurs, and proprietary functions are linked to commercial firms. However, little is known about the extent to which these actors are involved. Additionally, it is not clear if the actors' activities cross to other infrastructure elements. Thus, I set out to examine the creation of each infrastructure element and the roles of the respective actors involved. Then, I examine the interactions of these elements, especially in light of any actors that play roles in the creation of multiple infrastructure elements.

METHODS

I use a 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 (Yin, 2008; Eisenhardt, 1989). This study uses the framework of infrastructure for entrepreneurship established by Van de Ven (1993) as its foundation by treating each infrastructure element as an embedded unit of analysis within the case (Yin, 2008). Using this technique, I analyzed the data for each infrastructure element separately and then across elements. Thus, the creation and the configuration of a infrastructure for entrepreneurship was examined iteratively as elements developed (Eisenhardt, 1989).

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 have a size of less than 100 nanometers (National Science and Technology Council, 2000a). The prefix nano- means ten to the minus ninth power, or one-billionth. Therefore, a nanometer is one-billionth of a meter, about 1/80,000 of the diameter of a human hair, or the width of approximately three to ten atoms[1]. Nanotechnologists manipulate single molecules, atoms, and structures at the nanoscale. While nanotechnology is smaller than technology at the micron level by a factor of ten, this does not mean that engineers are simply shrinking things down to a smaller scale (National Nanotechnology Coordination Office, 2007). As mentioned, the physical properties of nanoscale molecules are different from those at a larger scale and scientists are going back to the lab to understand these properties and their ramifications. For example, the

[1] Andrew Hunt, founder of nGimat (one of the earliest nanotechnology firms), illustrated the nanometer by saying, “A football is to the earth what a nanometer is to a football.” (NSTI Nanotech Conference 5/22/2007 “The Evolution of Nanotech’s Business Model.”)

manipulation of carbon atoms into a form called buckminsterfullerene, or "buckyball" as it is commonly called, yields a strong structure which is resilient and flexible unlike large carbon structures such as graphite or diamond (IEEE, 2006b). The creation of new nanoscale substances requires new knowledge. This knowledge has been transformed into nanotechnology that has applications in almost all industries from cement to semiconductors (Woolley, 2010).

The recent emergence of nanotechnology offers a rare opportunity to observe a technology from its first conceptions through commercialization of products since it has no particular historical or industrial precedents (Rothaermel and Thursby, 2007). Similarly, nanotechnology provides the opportunity to observe entrepreneurship infrastructure creation and configuration distinctly. Although nanotechnology was built on existing knowledge, it required completely new public resources endowments, institutional arrangements, and proprietary functions to reach commercial products. As mentioned, the physical properties of matter at the nanoscale are different than that at larger scales, but these properties were not well understood before the 1990's (National Institutes of Health, 2008). Thus, the development of nanotechnology required basic knowledge and research to understand what the sciences had not previously explained. Unlike research conducted within existing fields, nanotechnology also requires integration across disciplines including physics, chemistry, and engineering (National Nanotechnology Initiative, 2006a). Depending on the research question, biology and astrophysics may also be included. This integration was not common at the time and few structures existed to facilitate such collaboration. Similarly, firms using nanotechnology must, by definition, manipulate matter at the scale of one to 100 nanometers (National Nanotechnology Coordination Office, 2007). However, before 1981, basic public knowledge on the successful manipulation of nanoscale materials was not prevalent in part because instrumentation to see or move matter at this level did not exist (National Nanotechnology Initiative, 2006b; Smalley, 1999). Thus, a starting point for nanotechnology related entrepreneurship is established as no earlier than 1981.

Data

This study uses quantitative and qualitative longitudinal data from archival sources written between 1976 and 2009 and 40 semi-structured interviews taking place between 2005 and 2007. Using two different types of data allow for triangulation, which is the inclusion of two or more 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, 1979). Using different data sources and collection methods increases the validity of the results (Singleton and Straits, 2005).

Archival Data

Archival data collection started with a search of government, industry, science and technology documents to gain a range of perspectives. These organizations were sampled using participant lists from early nanotechnology themed conferences (e.g. Foresight Conference on Nanotechnology, NanoCon Northwest, Gordon Reseach conferences, and NSTI annual nanotechnology conference). However, data provided in one source were often limited leaving many questions unanswered (such as a list of the specific actors involved in an event). To clarify these questions, other data sources were sought and new data were collected using google and yahoo web searches. Data collection stopped when the saturation point had been reached at which additional data provided only marginal insights (see Eisenhardt, 1989: p545). Table 1 summarizes the archival data collected.

Government documents regarding nanotechnology were found to be published between 1985 and 2010. Government documents regarding funding include the timing of awards, recipients, and scope of studies. Other government documents, such as congressional testimony, describe the status of nanotechnology at the time, its development and key actors involved. Industry, technology, and science documents also provide data about contemporaneous events and actors such as funding opportunities inside and outside the government, professional associations, scientific conferences, technology workshops, entering firms (incumbent and new), standardization efforts, regulatory bodies, recent and proposed legislation, and opportunities for collective action to shape nanotechnology's development. Press releases document the announcement of nanotechnology advancements and proprietary activity in firms including patents and product launches. Using such data helped reduce retrospective bias from documents and interviews written or conducted later.

To reduce single source bias, I sought corroboration of data from multiple sources when possible. Using data from such a variety of sources is important since it allows a researcher to gain "distance" from the phenomenon and maintain objectivity (Strauss and Corbin, 1998; p. 44). In addition, each source offers a unique perspective and contributes distinct value to the study. Data were also verified in interviews with nanotechnology experts. In total, the archival data include over 11,000 pages of records from over 30 organizations in wide range of populations such as government, associations and groups, universities, media, market research firms, and other firms. Records include reports, technical papers, newsletters, media reports, websites, and press releases.

To determine when nanotechnology entrepreneurship occurred, I created a database of nanotechnology firms founded before 2006 from the archival data. Nanotechnology firms are single-business ventures founded to develop, produce, and sell nanotechnology products, with over 50 percent of their activity (i.e., products, R&D, other expenses, or revenue) at the nanoscale. This definition excludes service providers, captive producers, subsidiaries, divisions and spin-offs of existing firms, distributors, designers, and custom engineering firms. From an original list of over 3,000 potential nanotechnology firms, I identified 303 confirmed nanotechnology firms founded between 1986 and 2005. The headquarters' location (city and state) and dates of founding and death were recorded for each firm. I verified the database against that of other researchers. Any discrepancies were researched, but no additional firms were included as these did not have nanotechnology capabilities.

Insert Table 1 about here

Interviews

I conducted 40 semi-structured interviews with nanotechnology experts who were selected from government, trade associations, professors of nanotechnology, founders, CEO's, and employees of nanotechnology firms, current and former government employees directly involved in nanotechnology policy, and consultants specializing in nanotechnology application and commercialization. I identified participants at early nanotechnology conferences (1989-1999) using the conferences' proceedings. Using this list, 27 experts were chosen based on their contributions to early nanotechnology conferences. An additional 13 interviews were conducted with experts recommended by the original sample. Interviews were conducted between 2005 and 2007. The interviews started with a set of open-ended questions and progressed to free dialogue. Interviews lasted between 20 minutes and three hours and covered the topics of entrepreneurship, nanoscience and nanotechnology creation, commercialization and contemporary activities as well as the role of actors and institutions in the formation of the nanotechnology field. I carefully documented each interview and, when agreeable to the respondents, digitally recorded and subsequently transcribed.[2]

Analysis

I analyzed the data in recursive stages grounded by the current theory regarding entrepreneurship infrastructure (Glaser and Strauss, 1967). First, the data were coded for nanotechnology-related events and actions that occurred after 1959. Events consist of a particular time in which a distinguishable phenomenon occurs such as a trade show or ceremony (e.g. Lampel and Meyer, 2008; Oliver and Montgomery, 2008). The process led to the recording of over 600 events. Each event was then coded as public resource endowments, institutional arrangements, and proprietary functions using dummy variables for each. Events related to more than one infrastructure element were coded accordingly. For example, the National Science Foundation (NSF) awarding research and development funding to physicist Dr. Nano at Cornell University would be coded with both public resource endowments (basic research funding) and institutional arrangements (government agencies and legitimation). Actors involved in the events or actions were coded for the organization type and actor position (if available). In the example above, the NSF was identified as related to government, Cornell would be identified as a university, and Dr. Nano would be identified 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, the data identified as related to an element of infrastructure were examined for

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[2] In total, 19 interviews were recorded and transcribed.

patterns, trends and themes. Using a process method (Van de Ven and Poole, 2005), events 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, frequency of codings, and the change in frequency and percentage of events over time (Miles and Huberman, 1994). Initially, the creation of infrastructure element was analyzed separately as an embedded unit of analysis within the case (Yin, 2008). The findings were then compared to the findings form existing studies. Then, I further compared the data between the element types 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 (Yin, 2008; Siggelkow, 2001; Eisenhardt, 1989).

RESULTS

To tell the story of how an infrastructure for entrepreneurship developed in the nanotechnology market, I first concentrate on the three key elements singularly: public resource endowments, institutional arrangements, and proprietary functions. After establishing how each element developed, I then examine how these elements configure in the face of technology development, new nanotechnology firms, and commercialization efforts. I find that although the elements of infrastructure are developed and configured simultaneously, entrepreneurship does not wait until a critical mass of infrastructure is built. Each element is necessary, but not sufficient to support firm and industry formation. Additionally, no one actor controls or configures every element of infrastructure. In contrast, infrastructure develops in the space between the actors and elements.

Public Resource Endowments

Public resource endowments include basic scientific or technological knowledge, financing mechanisms, and a pool of competent labor (Van de Ven, 1993). Nanotechnology is considered “at the frontiers and intersections of many disciplines including biology, chemistry, engineering, materials, and physics” (National Science and Technology Council, 2004: 1). The fundamental endowments for nanotechnology were developed over the history of science, but notably manifested in the invention of the scanning tunneling microscope (STM).[3] 1959, Richard Feynman, physicist and Nobel laureate, gave a talk at the annual meeting of the American Physical Society being held at the California Institute of Technology, entitled, “There's Plenty of Room at the Bottom.” He stated that scientists should soon be able to create structures at the molecular (nanoscale) level (Feynman 1959). This is one of the earliest references to molecular (nanoscale) manipulation and is regarded by many involved in the field as the launch of nanotechnology[4]. Despite Feynman’s 1959 assertion that molecular scale manipulation was inevitable, twenty years later scientists could not manipulate nor control samples at the nanoscale--even though advances in microscopy enabled the identification of atoms. Without appropriate instruments to view and manipulate at this level, empirical research and development at the nanoscale was not possible. Scientists could not produce empirical evidence for the merits or weaknesses of nanotechnology. Technically, nanotechnology was still theoretical conjecture.

The STM was the first instrument that enabled scientists to observe, move, and modify a nanoscale sample in three dimensions (Woolley, 2010). The inventors, Gerd Binnig and

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[3] The development of nanotechnology’s infrastructure for entrepreneurship contains many actors. For ease of reading, Appendix 1 includes a list of acronyms used in this paper.

[4] The Feynman talk was overwhelmingly included in statements and reports from government officials (IWGN, NNI, DOE), professional associations (IEEE, Forsight, nanotech-now.com), and academic leaders, as well as in interviews with entrepreneurs.

Heinrich Rohrer, first submitted a patent disclosure that discussed the concept of scanning tunneling microscopy in January of 1979[5]. After refining the patent and creating a working prototype, they observed their first results on March 16, 1981 (Binnig and Rohrer, 1986). According to interviewees and published reports, not only was the STM the first evidence of nanotechnology innovation, but also it verified the possibility of nanoscale research as scientists were finally able to empirically examine what had earlier been only theory. As such, the invention of the STM provided legitimacy to the idea that nanotechnology was possible. Binnig and Rohrer's invention also provided the foundation for further development of nanotechnology. "It's the most important new tool to come out of physics or biology in this century," said Stuart Lindsay, Associate Professor of physics at Arizona State University (Pennisi, 1988).

Binnig and Rohrer were not the only scientists working to improve instrumentation. Almost a decade before the STM patent, researchers Russell Young, John Ward, and Fredric Scire worked on a related technology, field-emission microscopy, at the National Bureau of Standards (NBS, now called the National Institute of Standards and Technology or NIST[6]). Binnig and Rohrer (1986: 392) reveal that these researchers "came closer than anyone else" to inventing the STM. However, the NBS researchers did not advance the resolution to the nanoscale and in 1971 management at NBS canceled their project (Villarrubia, 2001; Binnig and Rohrer, 1986). Binnig and Rohrer's patent reference four publications, three of which were authored by NBS researchers between 1966 and 1975 and the other by a researcher at Belgium's Université de Liège in 1979. Support for the creation of scientific and technological knowledge is traditionally considered the role of public institutions (Van de Ven, 1993; Michelson, 2005).

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[5] Data regarding the dates of the STM patent and its references are from the original patent (#4343993) and Binnig and Rohrer's Nobel lecture (1986). Subsequent data were confirmed through resumes and profiles of referenced inventors.

[6] The NBS was funded by the U.S. Department of Commerce.

However, the cancelation of the field-emission microscopy project at NBS is an example of how while supportive of R&D, the government may make choices that hinder scientific development. Arguably, the breakthrough launching nanotechnology into reality could have occurred several years earlier given the necessary support.

During the 1980's, five countries dominated the nanotechnology R&D funding scene: Japan, the U.S., the U.K., Canada, and China. In the following five years, ten more countries established nanotechnology programs. As more governments specified funding for nanotechnology, rhetoric converged towards a common language and legitimacy for nanoscale science increased. The amount of funding available to nanotechnology researchers worldwide began to increase in the 1990's. Table 2 summarizes government program spending on nanotechnology from 1991 through 2006. By 1991, the total cumulative amount of national government funding spent on nanotechnology R&D was less than $100 million worldwide, mainly distributed by the five countries with government sponsored nanotechnology research programs. By 1994, the cumulative funding had more than doubled to about $250 million and in the next three years it almost tripled to total $700 million, an increase of about 40 percent per year by 1997. While the increase appears substantial at first glance, the total R&D budget for the federal U.S. government reached almost $74 billion in 1997 (American Association for the Advancement of Science, 2002; Eiseman et al., 2002). Thus, funding provided by nanotechnology-specific programs totals less than one percent of the U.S. federal government's overall R&D spending.

In the 1970's, funding of R&D in the United States was shared almost equally between industry and government. Starting in 1980, industrial (or private) funding of R&D has surpassed government funding, which has continued to drop as a percentage of gross domestic product ever since (National Science Foundation, 2001). In fact, industrial funding of R&D increased rapidly in the last five decades. In 1976, the ratio of private to federal R&D funding was 1:1 compared to a 3:1 ratio in 2002 (Eiseman et al., 2002). Support for R&D shifted at this time from the public to private sectors.

Insert Table 2 about here

The emergence of nanotechnology is an example of the importance of the shift from government to industrial funding as industry started taking on the role of primary supporter of basic scientific research. IBM did not operate in the microscopy industry. Binnig and Rohrer created the STM to examine thin layers of insulating materials for use in other IBM products. They invented and constructed the STM because no substitutes existed. That is, they invented the STM to better accomplish their work, not to make a breakthrough patent, start a new industry, or revolutionize the world. In fact, IBM did not seek to commercialize the STM (personal communication with Christoph Gerber, 2009). IBM's innovation for competitiveness intersects its role as a financing mechanism of basic scientific and technical knowledge. Here, the creation of both public resource endowments and proprietary functions occurred in the industrial realm, not a public organization as traditionally thought.

Another foundational scientific breakthrough took place at IBM; the invention of the atomic force microscope (AFM) by Binnig (of STM fame), Christoph Gerber, and Calvin Quate. The AFM improved upon the STM by enabling scientists to see non-conductive material samples at the atomic (nano) scale, which had not been possible previously. The AFM allowed scientists to see molecular forces never before observed. A National Science and Technology Council report asserted the STM and AFM "provide the 'eyes' and 'fingers' required for nanostructure measurement and manipulation" (National Science and Technology Council, 2000b: 20). The

STM and AFM are fundamental innovations that have enabled countless other discoveries and inventions. In fact, in 1986, Binnig and Rohrer were awarded the Nobel Prize in physics for their invention of the STM five years earlier.

It is possible that other instrumentation innovations similar to the STM and AFM could have been invented with similar functions as other scientists grappled with the same questions and curiosities. However, both the STM and AFM were invented by scientists working at a supportive, resource-rich firm, IBM, that supported patent applications of these inventions and travel necessary to obtain scientific feedback and then recognition from the academic community (Weiss, 2007). In fact, IBM has the highest number of nanotechnology-related patents (Li, et al., 2007). Had the inventors worked in other organizations, we cannot be certain that the inventions would have had the necessary support or followed the same trajectory as seen in NBS's cancelation of a similar product.

During the early years of nanotechnology emergence, a majority of researchers at firms as well as universities did not seek funding to support their work under the guise of nanotechnology, but instead used traditional scientific disciplines and research programs. Table 3 shows that funding for nanotechnology research simply did not exist at this time. As mentioned earlier, R&D funding in general by the U.S. government steadily decreased after its peak during the space and arms races in the 1960's (National Science Board 2008). During the 1970's, overall R&D spending reached a plateau, with the decline in federal spending offset by an increase in the industrial sector. By 1979, industrial spending on overall R&D had overtaken federal spending in the U.S. In fact, the NSF estimates that industrial funding of nanotechnology research is comparable to or surpasses that of government support since its beginning (NSF, 2001). However, as the largest proportion of industrial spending went to pharmaceutical research and that of federal funding went primarily to defense programs, basic scientific researchers were still challenged to find research funding. Nanotechnologists Stanley Williams, a scientist at Hewlett-Packard, and Galen Stucky of University of California Santa Barbara's chemistry department describe the tension between established scientific disciplines and nanotechnology as funding for nanotechnology was "open competition with other research topics within various disciplines" (Williams and Stucky, 1999). Additionally, interviewees noted that because nanotechnology was not established or even recognized by most of the scientific community, those working in nanotechnology sought support within their traditional disciplines. For example, Japan started the first government funded program specifically related to nanotechnology in 1981 (Roco, 1999). Since the term "nanotechnology" had not yet gained dominance in parlance, the administration of Japan's Exploratory Research for Advanced Technologies (ERATO) program called it "ultrafine particles" research. To support further nanotechnology research, ERATO launched the "Nano-Mechanism" project headed by the Managing Director of Nikon, Mr. Yoshida in 1985. In 1986, ERATO funded the "Molecular Dynamic Assembly" project, led by Dr. Hotani, a professor at Teikyo University. The U.S. Department of Energy started R&D funding of nanotechnology in 1985 with a program on "nanophase materials" at Argonne National Laboratories. These programs exemplify the role of both public and private organizations in the creation of public resource endowments.

Insert Table 3 about here

Of course, public resource endowments were also generated by university researchers, especially those focusing mainly on creating novel molecules and atomic structures. Researchers at the University of Sussex, Rice University, MIT, Caltech, and Tokyo Science University worked on nanotechnology-related projects. One of the most important inventions was the buckyball by British scientist Sir Harry Kroto at the University of Sussex, with Richard Smalley and Robert Curl at Rice University in 1985 (e.g. IEEE, 2006a). The advent of the buckyball signified a breakthrough in nanotechnology as it was the first successful foray into nanoscale manipulation at the creation of nano-structures outside of chemical reactions. The process of creating the buckyball is also foundational for nanotechnology, since it is the basis for constructing a multitude of other nanoscale materials such as carbon nanotubes (IEEE, 2006b). These early technological innovations were thus critical to the nanotechnology infrastructure as they provided the tools for exploration and manipulation at the nanoscale and the development of the technology. In essence, without these early inventions and innovations, there would be little basic scientific knowledge on which to build nanotechnology.

Institutional Arrangements

Institutional arrangements provide the regulative and normative function of infrastructure by legitimating, regulating, and standardization (Scott, 2008). Several actors who contributed to the generation of public resource endowments in the previous section also acted to normalize the technology as well. For example, government and private funding of nanotechnology research signaled that these organizations supported continued activity in the field, in turn, helping to establish legitimacy for nanotechnology. While university researchers created public knowledge through nanotechnology courses and programs, they also built legitimacy for the technology by informing a broader audience of its merits and detractions. Other institutional arrangements include government agencies' organizing efforts, associations, standardization efforts, publishing houses and their journals (Scott, 2008).

The legitimacy of money

The Department of Energy (DOE) was the earliest government agency to sponsor nanotechnology research in the United States. In 1985, the DOE started a program researched what they termed “nanophase materials.” The National Science Foundation (NSF) acted as a substantial institutional arrangement in the building of infrastructure for nanotechnology entrepreneurship. The NSF’s Program Director for Engineering, Dr. Mihail Roco, participated in the organization’s earliest nanotechnology-related programs starting in 1991 with their ultrafine particle engineering program (see Table 1). After Roco became Program Director in 1995, he organized a group of researchers and experts from several government agencies, universities, and national labs to discuss a long-term plan for nanotechnology in the U.S (Roco, 2006). As a result, the NSF established a $10 million program, "Partnership in Nanotechnology: Functional Nanostructures,” in 1997. In 1998, Roco's informal group was formally designated the Interagency Working Group on Nanoscience (IWGN) by President Clinton as a planning committee for the advancement of nanoscience in the U.S. (National Science and Technology Council, 1999). By 1999, the IWGN included over 50 participants from a diverse spectrum of organizations including universities (e.g. California Institute of Technology, Cornell University, Rice University, Massachusetts Institute of Technology, Harvard University, University of California, Berkeley, and University of California, Los Angeles), national labs and research projects (e.g. National Aeronautics and Space Administration (NASA), the Jet Propulsion Laboratory (JPL), Los Alamos National Laboratory, and the Human Genome Project), government agencies (e.g. NSF, DOE, and Department of Commerce[DOC]), and firms (e.g. Hewlett Packard, IBM, Ford, Exxon, Merck, Dow, Monsanto, and Eastman Kodak) (Roco *et al.*, 1999). Through workshops, the IWGN formulated and proposed the National Nanotechnology

Initiative (NNI), a federal program to coordinate the multiagency efforts in nanoscale science, engineering, and technology (National Science and Technology Council, 2000b). The proposed budget was almost half a billion dollars, doubling the annual spending at the time (see Figure 1). In June, the U.S. Congress held hearings addressing nanotechnology, including the proposal for the NNI. Dr. Richard Smalley (inventor of the buckyball), Dr. Ralph Merkle (researcher from Xerox), and Dr. Eugene Wong (Assistant Director for Engineering at NSF) testified in Congress to support the NNI. What started as an informal group by the NSF Program Director became a significant piece of legislature with contributions from many stakeholders.

Insert Figure 1 about here

Although building over time, legitimacy for nanotechnology was formally affirmed on January 21, 2000 at Caltech, the site of Feynman's historical lecture forty-one years earlier when President Clinton announced the implementation of the NNI with a planned budget of $465 million. The Nanoscale Science, Engineering and Technology (NSET) took the initiative to individual government agencies to gain support and assistance in planning. The first government agencies participating in in the NNI included the DOE, DOC, Department of Defense (DOD), NASA, National Institutes of Health (NIH), and NSF. Nanotechnology had grown from an "impossible dream" to the focus of one of the largest federal science initiatives in history.

The implications of the NNI were far-reaching and immediate. Several nanotechnology experts specifically stated that the passage of the NNI was one of the most important events in nanotechnology development. For example, "The success of the [nanotechnology] 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 1960's" (Foster et al., 2006: 16). When the first year of the NNI appeared successful, President Clinton requested that the fiscal year 2001 budget include a $225 million (83 percent) increase in the federal government's investment in nanotechnology R&D through the NNI. 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, but it was the creation of the NNI that acted as the culminating decisive event.

The U.S. was not along and by the year 2000, 15 countries had funded nanotechnology projects. However, the level of funding did not grow until after the U.S. government announced the NNI in 2000 (see Table 2 and Figure 1). Table 2 shows that in the three years after 2000, the number of countries with national government nanotechnology research funding programs more than doubled from 15 to 35. Between 2000 and 2003 worldwide spending on nanotechnology R&D increased almost 400 percent. In 2005, annual national government nanotechnology research funding in Japan reached $950 million, just behind U.S. nanotechnology research funding of $1.2 billion. In 2002, the European Commission adopted their Sixth Framework Programme that allocated $1.8 billion to nanotechnology research over four years (Europa, 2007). The striking difference between the rate of funding increase before and after the year 2000 indicates that the year was a turning point not only for U.S. federal government spending on nanotechnology, but also nanotechnology support at multiple levels around the world.

Setting standards

The construction of standards in an emerging domain offers evidence of normative exercises that institutionalize a field, such as the creation of a common language (Scott, 2008).

Standards proved to be a difficult hurdle for the nanotechnology community. One reason for the difficulty was a lack of agreement on the definition of nanotechnology by key stakeholders. In 1974, Professor Taniguchi of Tokyo Science University first used the word nanotechnology to mean, "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). Eric Drexler used the term in reference to new technology at the molecular level, especially that of machines (Drexler, 1986). The IWGN's definition includes synthesis, processing, modeling, simulation, characterization, manipulation, and conceptualization of nanostructures (Howek, 2000). Some used nanotechnology to mean anything smaller than 100 nanometers that has novel properties (e.g. the NNI and US Presidential Council of Advisors on Science and Technology [PCAST]), while others required the ability to manipulate individual atoms and molecules (e.g. the NSF). Without agreement on what constituted nanotechnology, difficulty arose in determining those organizations qualified as nanotechnology and those that did not. This is especially important for the funding agencies that needed precise and consistent criteria for funding decisions.

With contention and disagreement, the creation of formal standards for nanotechnology did not occur early in the creation and configuration of the infrastructure. It was not until 2003 when the first major standardization efforts occurred. That year, the Institute of Electrical and Electronics Engineers (IEEE) launched effort to create standards for electrical test methods for individual carbon nanotubes. The IEEE is an international organization that may have led to its success in determining agreeable standards since the debate took place around the world. To do so, the IEEE Council enlisted the coordination of 65 nanotechnology experts from ten countries (IEEE, 2003). Separately, China created the United Working Group for Nanomaterials standardization in December 2003 with similar goals. The American National Standards Institute in the United States and the British Standards Institute in the United Kingdom, both private non-profit organizations, independently created committees to review nanotechnology standards in 2004. At the same time, the Chinese government proposed standard terminology for nanotechnology and the National Bureau of the State Food and Drug Administration (SFDA) proposed nanotechnology product standards (Institute of Physics- Chinese Academy of Sciences, 2007). Additionally, the Japanese government and the European Committee for Standardization (CEN) created working groups to investigate the need for standards. In 2005, the International Organization for Standardization (ISO) and the CEN establish formal technical groups to create standards (TC 229 and TC 352, respectively). The two organizations determined that many topics of concern intersected and they decided to collaborate their efforts into the TC 229. By the end of 2010, 34 countries had participated in TC 229 and 11 countries had agreed to observe these standards. However, the ISO has 162 member (International Organization for Standardization, 2011) countries leaving 151 countries who have not agreed to the ISO/CEN nanotechnology standards, many of which are involved in nanomanufacturing. A lack of consistent and agreed upon standards for the manufacturing of nanoscale materials or the manufacturing of goods containing nanotechnology is dangerous as the characteristics of some new materials are still unknown. This lack of knowledge leads to unsafe products and working conditions. With the increasing globalization, a lack of consistent, agreed upon standards would endanger all.

Coming together – associations and groups

Industrial, scientific, and 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 et al., 2002). In particular, associations can facilitate (or inhibit) the development of learning, knowledge dissemination, and legitimacy for a nascent technology (Sine et al., 2005; Aldrich and Ruef, 2006). Existing organizations, groups or associations that became involved in nanotechnology include the American Chemical Society (ACS), Semiconductor Manufacturing and Technology Institute (Sematech), the Semiconductor Research Corporation (SRC), and IEEE. For example, the ACS was founded in 1876 started symposia regarding nanotechnology in 1996 (Chow and Gonsalves, 1996). Sematech and SRC are two of the leading semiconductor industry organizations. Both started to formulate nanotechnology roadmaps in 1998. IEEE created a nanotechnology council in 2002 to coordinate the scientific, engineering, and industrial applications of nanotechnology. That same year they started work to develop nanotechnology standards (IEEE, 2011).

Associations also supported proprietary functions. New professional organizations supporting nanotechnology continued to be founded and several web-based organizations were created as portals for nanotechnology information, resources, and the supply chain. Several scientific societies merged in 1997 to form the Nano Science and Technology Institute (NSTI) with education and business development as its primary goals. By 1998, the NSTI had started the first international nanotechnology conference hosting business and technical presentations, early-stage firm presentations and reviews, expert panels, and various exhibitors. The NSTI is the first evidence of a nanotechnology-related professional or trade association.

As the knowledge and curiosity about nanotechnology rose, along with the passage of the NNI in 2000, several organizations entered the information market by offering aggregated information on nanotechnology stakeholders. Lux Capital Group, LLC was formed in March 2000 to research investments in nanotechnology. In 2001, the founders of Lux, created the NanoBusiness Alliance as the first association founded to advance the emerging business of nanotechnology and micro-technology. Nanotech-now.com started in 2000 to accumulate and analyze the latest nanotechnology news and developments to create reports and provide related consulting services. SmallTimes Media was founded in 2001 to collect and analyze business and technology data, offering an online repository of nanotechnology business news. Specific to investing in nanotechnology firms, the International Business Forum created a conference in 2002 bringing together venture capitalists with private equity investors, corporate investors, institutional investors, technology transfer experts, academic, government and corporate research scientists, firm executives, and government agencies. Atomworks started the same year to develop a regional resource network of science and industry leaders in the Midwest to promote nanotechnology growth, and provide educational and public awareness resources. Other firms, such as AZoNano and NanoVIP started in 2003, competed with similar business models to nanotech-now.com. All of these organizations consolidated information from other sources regarding developments in nanotechnology and disseminated it to a large audience, thus increasing the diffusion of knowledge.

Discipline or technology based journals provide an outlet for research and facilitate the dissemination and growth of knowledge (Lounsbury and Crumley, 2007). As such, new journals can act as institutional arrangements. Before nanotechnology specific journals existed, researchers in the field published in traditional discipline based journals such as *Physica, Physical Review Letters, Journal of Physical Chemistry*, and the *Journal of Chemical Physics*.[7]

[7] These journals were chosen as examples from the bibliography of the Nobel lectures from Dr. Binnig and Dr. Rohrer (1986) and Dr. Smalley (1996).

The number of articles related to nanotechnology grew (Youtie et al., 2008), new journals were created. For example, the first nanotechnology focused journal was created in 1990 when the Institute of Physics in the U.K. began publishing *Nanotechnology* to showcase nanoscale science and technology research worldwide (Foresight, 1990). The *Nanotechnology* journal incorporates research on fundamental physics, chemistry, and biology research at the nanoscale. In 1999, the *Journal of Nanoparticle Research* was created under the editorial guidance of Mihail Roco. After the announcement of the NNI, several new journals arrived. For example, ACS created the journal *NanoLetters* in 2001 to report on theory and practice in nanotechnology. They added the *ACS NANO* in 2007 to address the interface of nanotechnology research across disciplines. The *Journal of Nanoscience and Nanotechnology* was created in 2001; the *Journal of Nanotechnology* arrived in 2002; the *Journal of Nanotechnology Law and Business* arrived in 2005; and *Nature Nanotechnology* and *NANO* started in 2006. The journals provided information and news related to nanotechnology that was otherwise scattered and difficult to obtain.

The development of legitimacy for nanotechnology was not a smooth path. Several organizations have been founded to bring the risks of nanotechnology to the forefront and improve the understanding of the social and ethics aspects. Groups especially prominent for their challenge of nanotechnology were the Foresight Institute and the Center for Responsible Nanotechnology. Eric Drexler and his former wife, Christine Peterson, founded the Foresight Institute, the first nanotechnology association, in 1986. The Foresight Institute became a leader in identifying, evaluating, and promoting public policies to maximize the benefits and minimize the disadvantages of nanotechnology, as well as educating the public. However, Drexler's actions show the dual face of institutional entrepreneurs. He also published *Engines of Creation,* which supposedly described the potential implications of manipulating at the nanoscale. Published in 1986, only three years after the market introduction of the STM and the same year as the invention of the AFM, the book was not based on empirical scientific research, but instead on theoretical predictions and imagination. Drexler (1986) warns that nanotechnology has the potential to create "grey goo," a mass of self-replicating robots that consume all matter and end life on Earth. Although scientists have dismissed the grey goo hypothesis as impossible, the idea has become the fodder for countless science fiction stories.[8] Both the Foresight Institute and the book have received heavy criticism due to the lack of empirical research to support their claims. As with criticisms of Feynman's speech, doubts about nanotechnology's possibilities continued. These indicate that the early development of nanotechnology was not entirely smooth and positive.

Both information and misinformation were distributed by and to people who did not have technical knowledge in the nanotechnology field, which make it difficult to ascertain the veracity of the data. Organizations started addressing this problem. For example, the Center for Responsible Nanotechnology (CRNano) was founded in 2002 to examine the societal implications of nanotechnology. Michael Crichton published the fiction book, "Prey" that depicts nanoscale robots taking over the earth. Twentieth Century Fox bought the rights to the book and planned to produce a movie in 2004 (Vergano, 2004). However, the book was based on what CRNano called, "not very good science" (Center for Responsible Nanotechnology, 2008). Scientists voiced their concern over the movie misleading the public. Other voices were heard. As of 2011, the movie has not been released. However, the book, in part, prompted Prince Charles of England to voice concern over the possibility of self-replicating nanorobots in a 2003 public statement that generated substantial controversy (BBC, 2004). Similarly, in 2004,

[8] In a 2004 Nature journal article, Drexler admitted that he wished he had never used the term (Giles, 2004).

the group Topless Humans Organized for Natural Genetics (THONG) began protesting nanotechnology conferences and the Chicago Eddie Bauer store that carries pants made using nanotechnology (Lovy, 2005). Although the two protests were reported by the U.S. national news media, the group did not continue their efforts against nanotechnology. Understanding the risks of nanotechnology continues to be a concern; one to which the 2010 NNI budget allocated $88 million out of $1.64 billion, or five percent (National Science and Technology Council, 2009).

Proprietary Functions

Proprietary functions in the infrastructure initially took place in incumbent firms, especially those working to create knowledge and technology, as discussed in the public resource endowments section of this paper. The location of the early innovations and knowledge appropriate activities provides insight into the infrastructure development process. In contrast with commonly depicted academic origins of technological advancement, most of the major breakthroughs in nanotechnology were generated by existing non-academics working in firms across a diverse array of industries. Thus, the appropriate of those breakthroughs were closer to commercialization than if they were created outside of industry. For example, IBM not only created public resource endowments of basic knowledge and technology, but also appropriated these by advancing the technology in their product portfolio. Although IBM did not try to commercialize the STM and AFM, they did apply this technology to the production of semiconductors and other electronic parts.

Patent data also indicates industry driven innovation in nanotechnology. Of the 61 nanotechnology-related patents issued by the United States Patent and Trademark Office

(USPTO) in the 1970's, the majority were issued to IBM, US Navy, and Eastman Kodak (Chen et al., 2008). In 1982, both RCA and Texas Instruments (TI) were awarded patents for manufacturing methods and instrumentation that reached the nanoscale.[9] However, instead of occurring in related industries to the nascent technology (Carroll et al., 1996; Klepper and Simon, 2000), the early nanotechnology innovations occurred in industries outside of the focal firms' industry in the industries of the firms' suppliers. IBM, US Navy, Eastman Kodak, RCA and TI innovated upstream out of necessity – the items that they deemed necessary to advancement in their own products did not exist. Thus, proprietary functions in the infrastructure for entrepreneurship in a nascent market may not be industry specific, but rather technology specific. These inventions, while building public resource endowments, also developed the supply chains of the firms in which they were created. These incumbent firms shaped the foundation of nanotechnology, but neither concentrated on commercializing this technology nor attempted diversification into the industry of their breakthroughs.

New firms entered the nanotechnology field in 1987. That year, Digital Instruments was founded to license IBM's STM technology. A *de alio* firm specializing in the recently invented AFM entered the nanotechnology arena in 1987, MTS NanoInstruments Inc. The next two *de novo* nanotechnology firms, founded in 1988, were also instrumentation firms. However, the number of nanotechnology firms did not grow quickly. Figure 2 depicts the findings from

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[9] The next three breakthroughs in nanotechnology also occurred in existing incumbent firms in tangential fields: the creation of the nanoscale IBM logo in 1989, the invention of the atomic switch by Schweizer and Eigler at IBM in 1991, and the discovery of the nanotube by Sumio Iijima at NEC in 1991. In 1989, two IBM scientists, Don Eigler and Erhard Schweizer, playfully manipulated 35 individual xenon atoms to create the world's smallest logo, reading "IBM" three nanometers tall. Not only was this the first successful example of manipulation and movement of atoms individually instead of *en masse*, but this was also the first successful attempt by a commercial firm to manipulate matter at the nano-level. As IBM scientists invented the STM and AFM, the xenon atom manipulation breakthrough solidified IBM's position as the leader of nanotechnology innovation. Other large corporations pursing nanotechnology-related R&D activities in the 1990's include Beckman Instruments, Dow Chemicals, DuPont, Eastman Kodak, Hewlett-Packard, Hughes Electronics, Lucent, Motorola, 3M, and Sun Microsystems. In Japan, six large firms developed nanotechnology by actively funding its R&D: Hitachi, NEC, NTT, Fujitsu, Sony, and Fuji Film.

analysis of the database of nanotechnology firms showing the number of firms founded and the total number of nanotechnology firms (density) surviving each year from 1987 through 2004. By the end of 1993, only ten nanotechnology firms existed in the U.S. The majority of these were instrumentation manufacturers (60%) with the remainder operating in the materials industry. Until 1996, fewer than ten new nanotechnology firms were founded each year. Given the youth of the technology and its lack of legitimacy, resources, and knowledge, coupled with the high cost of nanotechnology development, it is no surprise that few entrepreneurs established new firms. The trend started to change in 1996 when 22 new nanotechnology firms were founded. By the end of 1999, 116 firms had been founded to produce nanotechnology products of which 35 percent based in the materials industry and 25 percent in the instrumentation industry. The number of nanotechnology firms founded increased substantially in 2000 and 2001, coinciding directly with announcements about the NNI creation. In 2000, 32 new nanotechnology firms were founded, followed by 43 the next year.

Insert Figure 2 about here

Venture capital (VC) can aid in the formation of new firms and in the development of a new technology (Avnimelech and Teubal, 2006). Venture capitalists not only contribute financial resources, but also they help build legitimacy of an emerging community or field (Aldrich and Ruef, 2006). However, venture capitalists seek investments from which they can obtain a high return in a relatively short amount of time, requiring a proven technology and products.[10] Experts interviewed observed that nanotechnology firms tend to not have products or revenues because they often have complicated technological issues to resolve which may require

[10] Venture capitalists usually invest in a company after it is formed, not before or during formation (ATP Economic Assessment Office, 2011).

considerable time before product launch. Therefore, investing in early stage nanotechnology firms is less appealing for venture capitalists.

VC firms did not significantly fund nanotechnology firms until the year 2000. Figure 1 and Table 2 shows the aggregation of data about worldwide nanotechnology activity from 1991 through 2006. As shown, the cumulative amount of U.S. venture capital funding to nanotechnology firms through 2000 totaled about $350 million. In 2001 alone, the amount of VC funding to nanotechnology firms climbed to $163 million and more than doubled to $386 million in 2002. These staggering increases happened despite the dot-com crash from 2000 through 2002 during which overall venture capital funding dropped from a high in 2000 of about $150 billion to less than $50 billion. Figure 3 shows the amount of all VC funding in billions as bars and the percentage of VC funding that went to nanotechnology firms. As the amount of overall VC funding decreased, the percentage given to nanotechnology firms continued to increase. Figure 3 shows how the percentage of venture capital given to nanotechnology firms out of all funding jumped from less than a half of a percent in 2001 to almost two percent in 2002. Other investments became less attractive, while the opportunity to invest in nanotechnology products gained appeal (Hebert, 2006). In 2003, Intel projected that it would earn $20 billion in cumulated revenues from nanotechnology (National Science and Technology Council, 2003). About 70 percent of all nanotechnology start-up companies worldwide were located in the U.S. at that time. In 2004, Lux reported that 63 percent or 19 of the 30 companies comprising the Dow Jones Industrial Average were funding R&D in nanotechnology (Lux Research Inc., 2004). Additionally, nanotechnology firms were closer to product commercialization than ever before. Thus, VC firms shifted their strategy to target more nanotechnology firms (Hebert, 2006).

Insert Figure 3 about here

Building the Infrastructure for Entrepreneurship

Earlier sections detailed the development of the three main elements to the infrastructure for entrepreneurship. This is only part of the story. The earlier sections mention how each of the elements of infrastructure was not created in isolation, but required development in other elements as well. This supports importance the coevolutionary perspective of organization-environment change (e.g. Baum and Singh, 1994; Rosenkopf and Tushman, 1994; Lewin et al., 1999). However, here it is evident that the coevolution was not isolated to the technology, but was systemic. The following section looks at the implications of this coevolution for the infrastructure and entrepreneurs.

Before the year 2000, the infrastructure for nanotechnology entrepreneurship was frail, yet building. Fewer than ten countries were funding nanotechnology research projects, few U.S. government agencies participated in or sponsored nanotechnology projects, and venture capital for nanotechnology firms remained miniscule. However, from 1990 to 2000, the number of nanotechnology firms in the U.S. grew from four to over one hundred and fifty. Thus, entrepreneurship in nanotechnology did not occur after a wealth of environmental munificence accumulated. Instead, the entrepreneurs helped create and configure infrastructure for future entrepreneurs. For example, James von Ehr founded the nanotechnology firm Zyvex in 1996. In an interview, he stated how observing the lack of support and legitimacy for nanotechnology in Texas motivated him to work with industrial, academic, and governmental constituents in the field to create the Texas Nanotechnology Initiative in 2000. Von Ehr went on to testify to congress about nanotechnology in 2003 and serve on the Nanotechnology Technical Advisory

Group (NTAG) to PCAST. Similar stories can be found in the biographies of several nanotechnology entrepreneurs.

The configuration of the infrastructure for entrepreneurship is intertwined with entrepreneurship itself in many ways. Figure 4 depicts the configuration of the infrastructure through the interactions between elements and their creators. The foundational three elements of infrastructure for entrepreneurship are arranged equidistant from each other. Under each element is a list of their main functions based on the work of Van de Ven and colleagues (e.g. Van de Ven 1993; Van de Ven and Garud, 1989; Aldrich and Fiol, 1994; Tassey, 2000). The data indicates the primary organizations and institutions responsible for each function and these are listed to the right of the function. Instead of separate roles for each actor, many actors were responsible for multiple functions across more than one infrastructure element, which blurred the boundaries of their organizations. For example, previous research has emphasized the role of universities and public organizations in the creation of public resource endowments. However, in nanotechnology, incumbent firms were critical to this part of infrastructure development. Similarly, institutional arrangements are usually considered the role of government agencies. Here we see that non-government organizations were quite involved in creating institutional arrangements. These organizations went beyond their usual boundaries and roles. Without this boundary crossing behavior, the creation of some elements of infrastructure for nanotechnology entrepreneurship would have altered considerably, if created at all.

Organizations that cross boundaries to develop infrastructure are integral to the process. A sample of cross-element functions are listed between the elements. Although the elements developed in tandem, they also were embedded in each other. This coevolution indicates that the infrastructure for entrepreneurship did not develop solely reliant on one element, but rather the space between the elements where it configured. Also, notice the bi-directional arrows connecting the elements that indicate that the configuration process is not uni-directional. Changes in one element not only influenced the development of the other elements, but also rippled through the infrastructure. For example, the NNI is a public resource endowment that supports the generation and dissemination of knowledge. The NNI does this by supporting nanotechnology research in both firms and public organizations. Thus, the creation of the NNI directly influences the creation of public resource endowments, but functions as an institutional arrangement to help build legitimacy for the field and support the commercialization of nanotechnology products in firms, thus building the proprietary functions of infrastructure. Similarly, Japan's ERATO programs funded research at both corporate and academic labs and the IWGN brought together government officials, firm executives, and science professors.

In a similar vein, the earliest entrepreneurs (1987-1994) worked closely with incumbent firms and university researchers to develop and commercialize inventions. By examining the resumes and website profiles of the firm founders, I found that of those nineteen firms, seven (37 percent) were founded by university professors. Of the others, two were started while the founder(s) was a university student, one was a spin-off form a national laboratory, and another was a spin-off from one of the other early nanotechnology firms. These firms exemplify the role of public resource endowments in the proprietary function of the infrastructure. Without public resource endowments such as scientific knowledge, the early firms would not have been founded. These firms created also the upstream foundation on which other nanotechnology firms could rely (Woolley, 2010) the market infrastructure necessary for business. At the same time, entrepreneurs such as Von Ehr worked to change the institutional arrangements in state and local government. Thus, their actions transcend proprietary functions into institutional arrangements and public resource endowments. By 2002, over 22 regional nanotechnology alliances existed between academe, government, and industry and seven states had both economic nanotechnology stimulus initiatives and academic nanotechnology initiatives.

The interlacing of proprietary functions and public resource endowments is especially prominent in university-firm relations. Universities supported proprietary functions through research collaborations, user facilities, and technology transfer offices while firms conduct foundational scientific research and fund university research. For example, the NSF sponsored the creation of user facilities such as the National Nanotechnology Users Network (NNUN) in 1993. The user facilities were often housed on or near the campus of a research university and include expensive equipment often necessary for nanotechnology research. Some universities allow firms to rent a portion of the facilities in exchange for payments or intellectual property thus blurring the boundaries between public and proprietary knowledge. Other examples of such boundary obfuscation include firm sponsorship of basic science research and the commercialization of university sponsored research through technology transfer offices.

Individually, each of the infrastructure elements plays an important role in the creation and configuration of infrastructure for entrepreneurship. However, infrastructure elements cannot stand alone. Without an interaction or cross-development activities, the fabric of infrastructure cannot be formed. Thus, it is the actions of people and organizations that cross boundaries and blend the elements that create and configure an infrastructure for entrepreneurship. Infrastructure for entrepreneurship is not a bundle of separate nodes, but exists in the space between the nodes or elements.

Discussion and Conclusion

This study takes a macro-perspective to examine the context of entrepreneurship by focusing on that which is based on a nascent technology. This paper contributes to our understanding of entrepreneurship by further explicating the components of infrastructure for entrepreneurship or those resources and structures that facilitate and constrain entrepreneurial action (Van de Ven, 1993). Evaluations of entrepreneurship articles published in top-tier management journals consistently find that such work focuses on firm or organizational levels of analysis, overlooking industry, field, or environmental levels (Chandler and Lyon, 2001; Crook et al., 2010; Dean et al., 2007; Ireland et al., 2005; Woolley, 2011). Other studies have similarly argued that this body of work increasingly neglects the context of entrepreneurship, focusing rather on the entrepreneur or the firm to the exclusion of other levels of analysis which has limited theory building in the field (Davidsson and Wiklund, 2001; Zahra, 2007). This study turns to the influence of context on entrepreneurship – specifically, how this context is created and configured.

As we have seen, the infrastructure elements developed in tandem and over time became more intertwined. The populations of organizations configuring infrastructure elements had also developed commensalistic and symbiotic relationships with each other. Commensalistic and symbiotic relationships are the cornerstones of organizational communities which are collectives of functionally inter-dependent co-evolving populations (Astley, 1985; Hunt and Aldrich, 1998). As such, we observe the creation of an organizational community during infrastructure development, an area of organization research that remains neglected (Aldrich and Ruef, 2006).

Although I started by examined the role of different actors on the creation of the three infrastructure elements, I found that it is in their interaction where infrastructure is configured. Each of the many people, organizations, and institutions involved in creating the nanotechnology infrastructure were highly interdependent to the extent that without their interaction, an infrastructure may not have been built. Thus, it is not the amount of resources within an element or the efficacy of its function that leads to infrastructure. Infrastructure configures because of these interactions that configure an infrastructure, in the space between the actors and elements where boundaries blur. This finding steps away from nodal or actor-centric view of organizational processes to a more systemic treatment of change.

Work has studied the value of dynamic boundaries for firms (Santos and Eisenhardt, 2009; Afuah, 2001), industries (Farjoun, 1994), and business groups (Khanna and Rivkin, 2006). This study draws attention to the importance of boundary crossing and obfuscation at the infrastructure level. Yet, the findings here highlight several unresolved issues. For instance, in the nanotechnology case boundaries became more, not less, obfuscated. This obfuscation enabled actors to access different elements of infrastructure. To what extent competition for infrastructure drove boundary obscuring itself? Future research into the relationship between boundary obfuscation and competition for infrastructure elements would develop this area. In some cases, the boundary obfuscation facilitated infrastructure configuration. This calls into question the value of boundaries both immediately and in the long run.

Practical implications include a contribution to understanding how entrepreneurs take context into account when making entry decisions. Previous research has focused on opportunity creation and recognition, while assuming that once an entrepreneur finds the opportunity, the context will support the decision. However, as seen here, an infrastructure for entrepreneurship may not be ready to support such activity. On one hand, how entrepreneurs evaluate the different elements of infrastructure for readiness and resource munificence of an area (geographic or industrial) has not been well studied. On the other hand, 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 have the choice of whether to wait for more infrastructure to be created or be part of its creation. Given the importance of both the context in which an entrepreneur starts a firm and the role that firm plays in changing the context, an entrepreneur's evaluation of firm-infrastructure alignment or fit may greatly influence founding decision making. Further research in both of these areas is encouraged.

Implications span each of the stakeholders in an emerging domain of activity. For incumbents, the study indicates opportunities to influence industries and fields outside of their focus to create complementary and symbiotic technologies. For universities, the study indicates that their relationship to incumbents is one of balancing rather than competing. For both, areas of most favorable opportunity in during field formation, that is, in upstream industries. Policy makers interested in developing a nascent technology in their location will can better understand which areas are lacking support by looking at the interactions of infrastructure elements.

Far from being policy contagion, policy to support nanotechnology development and entrepreneurship was not automatically or smoothly adopted across the world. In contrast to to entrepreneurs, policy to build an infrastructure for nanotechnology was not automatic or passive once forerunner countries signaled involvement. Even other countries' governments waited until a critical mass of infrastructure for entrepreneurship cumulated before embarking on policy entrepreneurship. Contributors to policy-making can also determine the ability of their region to support further entrepreneurship and determine which areas need public policy attention.

Multiple actors including universities, existing incumbent firms, entrepreneurs, venture capitalists, policy makers and social movements contribute to the building of infrastructure.

However, their degree of involvement varies as different needs and concerns are addressed, institutions enter or are created, and new challenges arise. Their roles change over time and are contingent on the actions of other actors in the field and their interactions. Further analysis of how roles change over time is needed

As with any study, there are limitations. As an individual case study, the results are not intended as generalizable across all cases. However, the depth of this study provides a rich development of the empirical process given the boundary conditions. Similar radical technological discontinuities include clean technology and health care. It is a worthwhile endeavor to study the development of infrastructure for entrepreneurship after other radical technological discontinuities, especially those that are not dependent on scientific breakthroughs.

Although the study examines the 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' life, which is a constrained time period in which to observe selection forces. This limitation, however, is mitigated by the length of time that nanotechnology itself has been developing, which has entered 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 continue to improve our knowledge of the context in which organizations emerge.

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TABLE 1
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	Lux Research	2000-2010	100
	Gartner Research	2004-2005	50
	NanoMarkets	2006	50
	Woodrow Wilson Center	2005-2010	100
Media	NanoTechWire	2005-2009	50
	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 & Other	PR Newswire	1981-2010	1400
	Other (articles, reports, lectures)	1976-2010	1000

TABLE 2
Summary of World-wide Nanotechnology Activity, 1991-2006

	1991	1994	1997	2000	2003	2006
Countries with Nano Initiatives	5	8	12	15	35	50+
Global Government Nano Spending (cumulative millions)	100	250	700	3000	10000	25000+
Global Government Nano R&D Spending (annual millions)	NA	NA	423	825	3000	5000+
US Government Nano Spending (cumulative millions)	5	100	250	500+	3000+	5000+
US Government Nano R&D Spending (annual millions)	3	50+	116	270	862	1300
US Government Agencies Involved	2	2	4	6	15	25
Venture Capital to Nano-Firms (cumulative millions)	0	4	50	350+	1250+	2750+

Note. -- figures are rounded

TABLE 3

Nanotechnology Research Programs Sponsored By National Government Agencies (1981-1998)

Year	Country	Agency	Program Title
1981	Japan	ERATO	Ultra-fine Particle
1985	Japan	ERATO	Nano-Mechanism
	United States	DOE	Nanophase Materials
1986	Japan	ERATO	Molecular Dynamic Assembly
	United Kingdom	DTI	National Nanotechnology Initiative (NION)
1987	Japan	ERATO	Molecular Architecture
	United Kingdom	NPL	Nanotechnology Techniques
1988	Japan	ERATO	Quantum Wave
	United Kingdom	DTI	LINK Nanotechnology Programme
1989	Japan	ERATO	Atomcraft
	Japan	ERATO	Electron Wavefront
1990	Canada		Semiconductor Nanostructure Project
	China		Climbing Project on Nanometer Science
1991	Japan	NAIR	Joint Research Center for Atom Technology
	Japan	MITI	Quantum Functional Devices
	Japan	MITI	Atom Technology
	United States	NSF	Ultrafine Particle Engineering
1992	European Union		Physics and Technology of Mesoscale Systems
	Japan	MITI	Ultimate Manipulation of Atoms and Molecules
1993	Australia	NRC	Nanotechnology Program
	Belgium		Nanotechnology Program
	Japan	ERATO	Quantum Fluctuation
	Spain		Nanotechnology Program
	United States	NSF	Nanoparticle Synthesis and Processing
1994	United Kingdom	EPSRC	Nanotechnology Materials Science
1995	European Union	ESR	Vapor-phase Synthesis and Processing of Nanoparticle Materials
	Japan	ERATO	Single Quantum Dot
	Singapore		Nanotechnology Program
	South Korea		Nanotechnology Program
1996	European Union		European Consortium on NanoMaterials
	European Union		Joint Research Center Nanostructured Materials Network
1997	European Union		European Society for Precision Engineering and Nanotechnology
	Finland	AoF and FTDC	Nanotechnology Program
	Germany	BMBF	Nanotechnology Program
	Japan	ERATO	Protonic NanoMachine
	United States	NSF	Partnership in Nanotechnology: Functional Nanostructures
1998	France	CNRS	Nanoparticles and Nanostructured Materials
	Sweden		Nanotechnology Program
	Switzerland		Swiss National Program on Nanotechnology
	United States	NSF	Synthesis, Processing, and Utilization of Functional Nanostructures
	United States	NSF	Instruments Development for Nano-Science and Engineering

NOTE. AoF = Academy of Finland; CNRS = Centre National de la Recherche Scientifique; DOE = Department of Energy; DTI = Department of Trade and Industry; EPSRC = Engineering and Physical Sciences Research Council; ERATO = Exploratory Research for Advanced Technologies; ESR = European Science Foundation; FTDC = Finnish Technology Development Center; MITI = Ministry of International Trade and Industry; NAIR = National Institute for Advancement of Interdisciplinary Research; NPL = National Physical Laboratory; NSF = National Science Foundation; NRC = National Research Council

FIGURE 1
Summary of Worldwide Nanotechnology Spending, 1991-2006

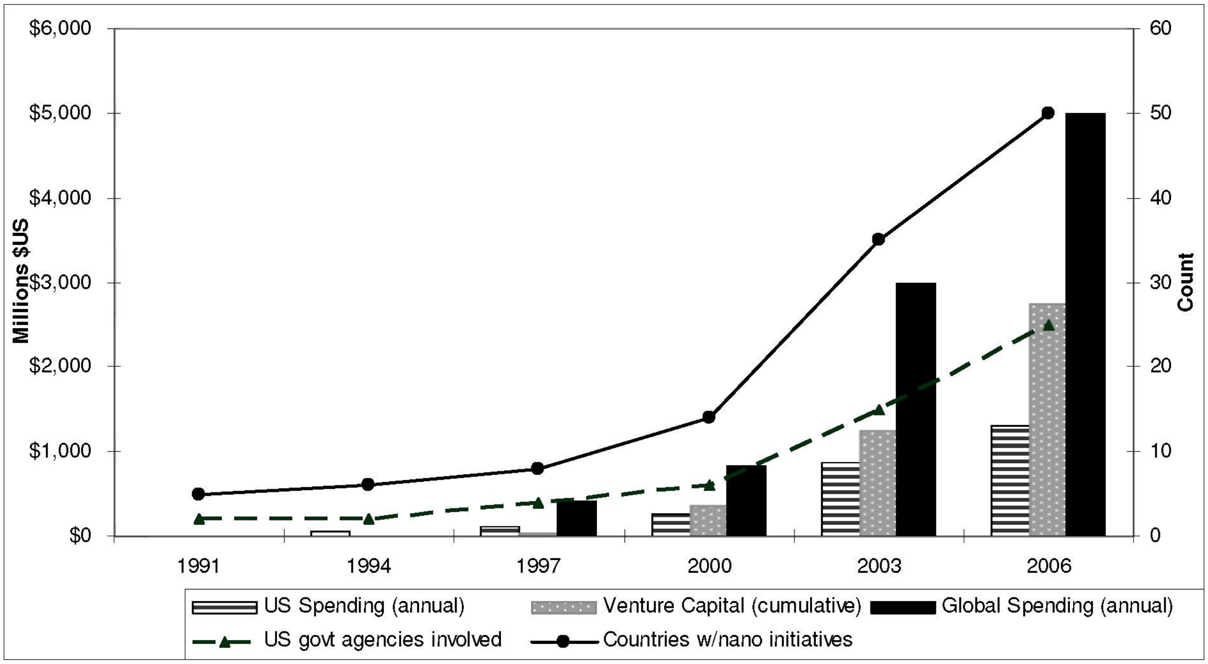

FIGURE 2
Number and Density of Nanotechnology Firms in the U.S. by Year (1987-2004)

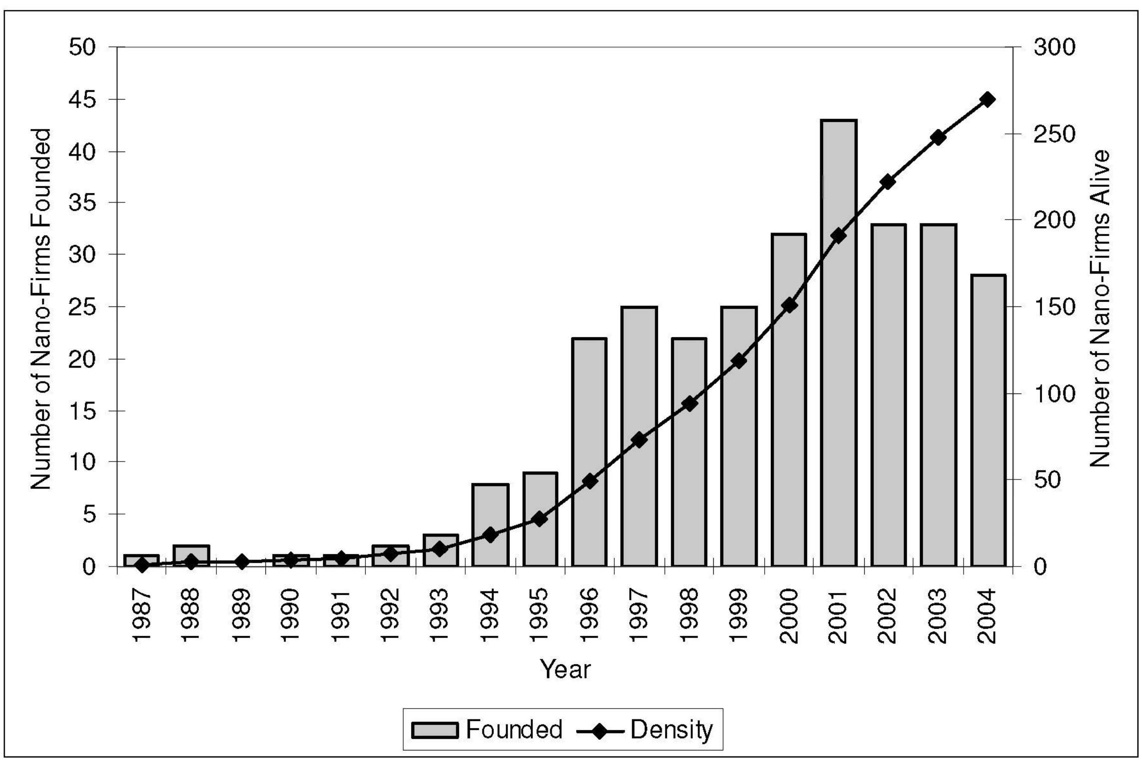

FIGURE 3
Venture Capital to Nanotechnology Firms as a Percentage of All Venture Capital Funding, Annually (1994-2006)

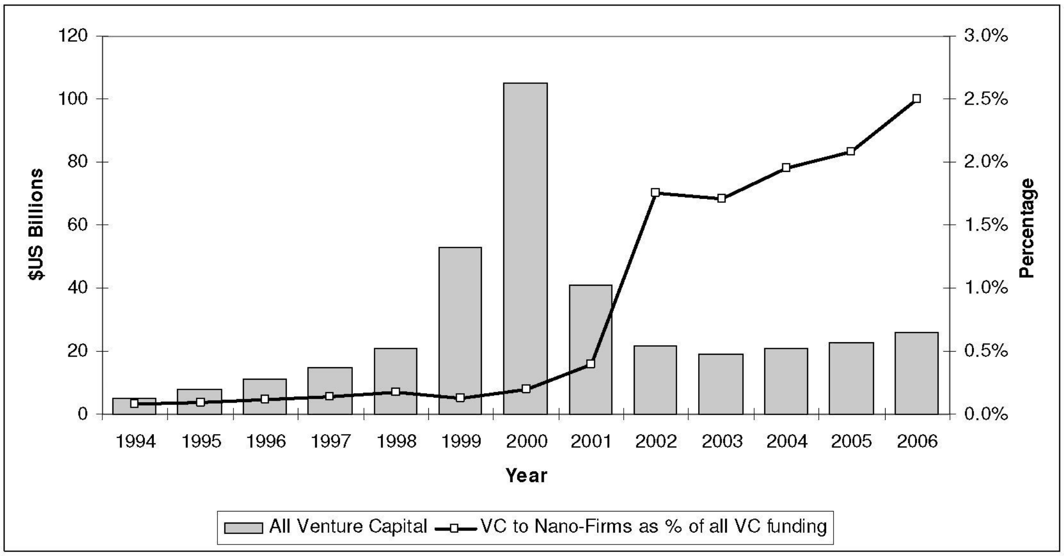

FIGURE 4
Infrastructure for Entrepreneurship Configuration

Public Resource Endowments	
Basic scientific knowledge	Universities
Technological knowledge	Universities and firms
Competent labor	Universities
Financing mechanisms	Public organizations (government and private)

- Firms conduct exploratory research
- Firms sponsor early research
- University-Industry collaborations
- University-Industry user facilities
- University technology transfer

- Governments creates agencies to support development of foundation technology
- Governments support small scale exploratory research
- Associations support human resource development
- Associations support basic science

Proprietary Functions	
R&D	Firms
Appropriation of common goods	
Commercialization	
Use of complementary assets	
Supply chain creation	
Support services	

- Government support of firms using the technology
- Government support of firm R&D
- Government support industry creation
- Entrepreneurship support (e.g. VC funding)
- Government, technical, and science associations creating industry standards

Institutional Arrangements	
Legitimate	Scientific and professional associations
Regulate	Government
Standardize	Standardization boards

Appendix A. Acronyms Used

AFM	Atomic Force Microscope
BFTP/SEP	Ben Franklin Technology Partners of Southeastern Pennsylvania
BMBF	Germany's Federal Ministry of Education and Research
Caltech	California Institute of Technology
CMOS	Complementary Metal Oxide Semiconductor
CNSI	California NanoSystems Institute
CNRS	Centre National de la Recherche Scientifique
CPSC	Consumer Product Safety Commission
CRNano	Center for Responsible Nanotechnology
DOC	Department of Commerce
DOD	Department of Defense
DOE	Department of Energy
DOJ	Department of Justice
DOS	Department of State
DOT	Department of Transportation
DHHS	Department of Health and Human Services
DOHS	Department of Homeland Security
EPA	Environmental Protection Agency
ERATO	Exploratory Research for Advanced Technologies
EUSPEN	European Society for Precision Engineering and Nanotechnology
FDA	Food and Drug Administration
FY	Fiscal Year
IEEE	Institute of Electrical and Electronics Engineers
IMM	Institute for Molecular Modeling
INDEX	Institute for Nanoelectronics Discovery and Exploration
ITC	International Trade Commission
IWGN	Interagency Working Group on Nanoscience, Engineering and Technology
JST	Japan's Science and Technology Agency
MIT	Massachusetts Institute of Technology
MITI	Ministry of International Trade and Industry
NASA	National Aeronautics and Space Administration
NIH	National Institutes of Health
NIOSH	National Institute for Occupational Safety and Health
NIST	National Institute of Standards and Technology
NNCO	National Nanotechnology Coordinating Office
NNI	National Nanotechnology Initiative
NNIN	National Nanotechnology Infrastructure Network
NNUN	National Nanotechnology Users Network
NRI	Nanoelectronics Research Initiative
NSET	Nanoscale Science, Engineering and Technology
NSF	National Science Foundation
NSTC	National Science and Technology Council

NSTI	Nano Science and Technology Institute
NTI	Nanotechnology Institute
OMB	Office of Management and Budget
OSTP	Office of Science and Technology Policy
PCAST	President's Committee of Advisors on Science and Technology
PHANTOMS	Physics and Technology of Mesoscale Systems
SBIR	Small Business Innovation Research
SFDA	State Food and Drug Administration, China
STM	Scanning Tunneling Microscope
STTR	Small Business Technology Transfer
SIA	Semiconductor Industry Association
THONG	Topless Humans Organized for Natural Genetics
TNI	Texas Nanotechnology Initiative
UCB	University of California Berkeley
UCD	University of California, Davis
UCI	University of California, Irvine
UCLA	University of California, Los Angeles
UCR	University of California, Riverside
UCSB	University of California Santa Barbara
USC	University of Southern California
USDA	United States Department of Agriculture
USPTO	United States Patent and Trademark Office