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The Role of Technological Systems in Community Creation: Emergence of a Nanotechnology Community, 1959-2004

DISSERTATION

submitted in partial satisfaction of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

in Management

by

Sang-Joon Kim

Dissertation Committee:
Professor Claudia Bird Schoonhoven, Chair
Professor Lynne Goodman Zucker
Professor Denis Trapido

2014

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DEDICATION

To

Parents

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The journey was long, but fruitful. Standing at the end of the road, I realize that there are many people to whom I am indebted for supporting me in this scholarly journey. Only the two words, "thank you," are not enough to reveal my inexplicable feeling of gratitude.

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I'd like to think back to the starting point of my journey. I confess that it would not be possible to make such a giant step for the journey without Professor Hun-Joon Park, Yonsei University. He always inspires me to explore new topics.

And my deepest gratitude to my parents and sister. Their support and encouragement surpass anything that I could ever imagine.

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WORKING PAPERS

Schoonhoven, C. B. & **Kim, S-J**. Where Do New Firms Come From? Science and Innovation Precursors of de Novo Population Emergence in Nanotechnology 1970-2004.

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Kim, S-J. Structure of Behavior: Understanding Diffusion Processes in the Individual Level.

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Kim, S-J. Achieving Attention-Based Temporal Ambidexterity in Technology-Based SMEs: Performance Implications of Focus Change in Resource Allocation.

Oh, H., Bae, J., & **Kim, S-J.** Taming Polysemous Signals: The Role of Marketing Intensity on the Relationship between Financial Leverage and Firm Performance.

Kim, S-J. On A focusing-balancing dilemma in SMEs: The impact of resource allocation on financial inflexibility and performance volatility.

Kim, S-J. The Role of Discourse in De-institutionalization of Stigma.

RESEARCH IN PROGRESS

Kim, S-J. & Seo, M-G. Non-monotonic Effects of Discourse on Online Collective Action. Write-up stage.

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CONFERENCE PRESENTATIONS

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Kang, R. & **Kim, S-J.** 2011. Investigating Temporal Ambidexterity: Focus, Switch, Cycle Duration, and Firm Performance. Presented at the Annual Meeting of the Academy of Management (BPS division), San Antonio, TX.

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Kim, S-J. 2007. Learning corruption: A Percolation-based System Dynamics Model on the Corruption Process. Presented at the 2007 Annual Meeting of Academy of Management (OMT division), Philadelphia, PA.

PROFESSIONAL PUBLICATIONS

Kim, S-J. & Kim, J-J. 2014. Social Construction of Impression Management: The Role of Work Experience in Implementing Female Employees' Impression Management. *Journal of International Trade & Commerce*, 10(1): 163-199.

Kim, J-J., & **Kim S-J**. 2013*. Positive Paradigm.* (In Korean) Book (ISBN 10-8998886464), Seoul, Korea: Kyobo Moon-go (a major Korean publisher).

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ABSTRACT OF THE DISSERTATION

The Role of Technological Systems in the Community Creation: The Emergence of the Nanotechnology Community, 1959-2004

By

Sang-Joon Kim

Doctor of Philosophy in Management

University of California, Irvine, 2014

Professor Claudia Bird Schoonhoven, Chair

This study explains how new science-based knowledge is adopted by diverse organizations, which over time creates the conditions for emergence of a new organizational community. I focus on the role of technological systems in emergence of a science-based community. A technological system is defined as regional sources of knowledge and competence that develop and diffuse technical and scientific knowledge in emerging fields of science. I argue that technological systems enhance the visibility of new science and novel technology, promote resource spillovers, assist identity construction, and attract entrepreneurs to apply the new technology to new business opportunities. As a result, many organizations originating in separate existing communities increasingly become involved in developing and commercializing a new technology, which over time, creates the nucleus for new community emergence. Focusing on emergence of a nanotechnology community in the U.S. between 1959 and 2004, I investigate that technological systems can emerge through scientific collaboration; size of technological systems can foster emergence of de novo organizations dedicated to the new knowledge; and technological systems can reinforce the knowledge flow between universities and industries to facilitate emergence of a new community.

First, I contend that scientific collaboration, defined as co-authorship based on new scientific knowledge, can lead to the emergence of technological-system formation. Specifically, it is found that intensity and heterogeneity of scientific collaboration speeds up the formation of technological systems. Second, the role of technological systems in community creation is discussed, arguing that size of technological systems, specified into depth (i.e. the number of components) and breadth (i.e. the number of subsystems), has impacts on community creation. The estimation results show that both depth and breadth increase the likelihood of de novo foundings and population differentiation. Last, knowledge flow between universities and industries is specified into knowledge streaking (collaboration ties) and knowledge leaking (citation ties). The estimation results reveal that knowledge streaking and inflow of knowledge leaking are positively related to the founding rate of new firms and the rate of population differentiation. Also, the relation between the inflow of knowledge leaking and community creation is reinforced by research centers.

CHAPTER 1

INTRODUCTION

This scholarly journey attempts to unpack mechanisms of community emergence. A community is defined as 'sets of diverse, internally homogeneous populations which depend crucially on the nature of the technologies on which the populations are based' (Astley, 1985: p. 224). Emergence of new organizational forms has been primarily studied within the context of the emergence of new organizations (Aldrich & Ruef, 2006; Astley, 1985; Ruef, 2000; Sorenson & Audia, 2005). From prior literature, we can identify two approaches in explaining the emergence phenomena of organizational forms: genealogical perspectives and organizational imprinting approaches. The genealogical perspectives emphasize the importance of prior experience in founding a new firm. That is, previous individual actions can affect future entrepreneurial behavior. Phillips (2002) assumed that organizational routines are a "blueprint," which may be transferred from parent organizations to progeny, via a founder's prior experience. Burton & Beckman (2007) focused on roles and positions, which become institutionalized over "incumbent generations," to conjecture that local firm histories influence founding a new firm.

In contrast, from a macro perspective, organizational imprinting deals with the roles of external environment in the emergence of new organizations. According to Stinchcombe (1965) and Romanelli (1991), new organizations are influenced by conditions in their external environment at the time of founding. Ecological studies have considered the macro-structural characteristics of the external environment which influence the birth rates of new organizations

(Hannan & Freeman, 1989). For example, Hannan & Freeman (1987) found that change in immigration can influence the birth rate of labor unions. These various imprinting arguments commonly maintain that environmental factors are powerful conditions important in the emergence and evolution of new organizational forms.

While these approaches may be applicable to emergence of a new community, the sole use of them may be at least a partial explanation. First, in the genealogical approach, we may explain emergence of a new community by clearly identifying who are the initiators for the new community and by tracing their actions taken for community creation. Yet, since a community is composed of diverse organizations which are interrelated, individual local organizations' histories should be less explanatory than the history of inter-organizational relationships. In fact, although DiMaggio (1991) historically illustrated the role of professional organizations in constructing an organizational field, he did not consider individual organizations as heroic predecessors, but rather emphasized the interactions between philanthropic foundations and art museums. Meanwhile, the imprinting approach looks helpful to understand emergence of a new community because communities can be influenced by the environment. However, communities themselves also constitute elements of the environment, enabling organizations within the communities to interact with each other. For example, Callon et al. (1992) identified the collectivity of diverse social actors who are networked for technology innovation, called techno-economic networks [1]. That is, communities are influenced by their environment, but simultaneously, they can construct their own structures through social interactions among diverse social actors.

[1] Techno-economic networks are defined as "a coordinated set of heterogeneous actors – public laboratories, technical research centers, industrial firms, financial organizations, users, and public authorizes – which participate collectively in the development and diffusion of innovation and which via numerous interactions organize the relationships between scientific-technical research and the marketplace" (Callon et al., 1992: p. 220)

In fact, Astley (1985) argued that relationships between the diverse organizations cannot be ignored in investigating at the emergence of a new community. In fact, community ecology, which explores relationships between several populations and explains how a community emerges and evolves, assumes that a community is composed of organizations whose origin populations are heterogeneous and inter-related (Astley, 1985; Ruef, 2000). Specifically, Astley (1985) posited that the community evolution corresponds to "the joint product of forces that simultaneously produce homogeneity and stability within populations and diversity between them" (p. 224). Accordingly, the mechanism for emergence of a new community is better understood by a focus on inter-relationships between existing organizations or populations (Aldrich & Ruef, 2006; Crane, 1972; Powell et al., 2005; Laumann, Galaskiewicz, & Marsden, 1978; Ruef, 2000; Audia et al. 2006), rather than on either the genealogical perspectives or the organizational imprinting approaches.

Social network theory helps further understand the interplay between multiple, diverse populations (e.g. Baum, et al., 2005; Simons & Robert, 2008; Strang & Soule, 1998; Barley, Freeman & Hybels, 1992). Some network studies attempt to relate to emergence of new organizational forms. For example, Barley, Freeman & Hybels (1992) illustrated multiple organizations and relationships in the biotechnology community and found that networks of inter-organizational alliances were integral to the structure of the community. Powell et al. (2005) focused on network configurations in studying the emergence and evolution of the life science field. They defined a field as 'a community of organizations that engage in common activities and are subject to similar reputational and regulatory pressures' (p.1134), i.e. the life sciences. Gulati, Sytch, & Tatarynowicz (2010) argued that individual actors' formation of bridging ties could eventually homogenize the information space and create a globally separated network. They specified the features of small networks in industrial clusters, which are characterized similarly to communities in terms of heterogeneous actors, inter-relationships, and evolutionary dynamics based on existing organizations or social actors. Specifically, they found that bridging ties between industrial clusters are important in cluster evolution, because they can reduce the disadvantages of small worlds and restore the heterogeneity of clusters.

In summary, community emergence can be understood as a product of inter-relationships across diverse populations. A community forms as diverse populations increasingly adopt the same knowledge through ongoing inter-organizational interactions. Deroian (2002) argued that the community through which an innovation is adopted by heterogeneous organizations constitutes preliminary conditions for market expansion. According to his argument, inter-organizational relationships convey a sufficient level of information about an innovation, which in turn suggest new areas for technology commercialization because a collective evaluation of the innovation is generalized.

Then, one can ask, how can new knowledge be disseminated and shared among social actors to create a new community? In my dissertation, I argue that there are organizing efforts of social actors, based on their inter-relationships. Specifically, I postulate that technological systems, which consist of organizations, practices, and institutions in academia or public sectors, can be a primary source of technological innovation, resulting in the emergence of a new community. Technological systems are defined as regional sources of knowledge and competence (i.e. the presence of local scientists, university educational programs, patents filed by regional organizations) that develop and diffuse technical and scientific knowledge in emerging fields of science. While technological systems are a structure drawn from mainly academia and governments, communities include for-profit organizations (firms, suppliers, and customers), and other organizations related to technology commercialization. Delineating technological systems from communities in terms of market mechanisms, I illuminate the significance of technological systems in understanding the process in which new knowledge enables to create a new market-based community.

In this dissertation, I argue that technological systems play a critical role in the process of community creation. Specifically, by dispersing relevant scientific knowledge across social actors and geographic regions, technological systems enhance the visibility of new science and novel technology, promote knowledge spillovers, assist identity construction, and attract entrepreneurs to apply the new technology to new business opportunities. As a result, many organizations originating in separate existing populations increasingly become involved in developing and commercializing a new technology, which over time, creates the nucleus for emergence of a new community.

Furthermore, I emphasize an aspect of social construction in technological systems. The consequences of technological systems actually are not new. The concepts of national innovation systems, regional/sectorial innovation systems, clusters, and milieu consistently suggest that the conception of these structures can help facilitate technological innovation and (regional) economic growth (e.g. Moulaert & Sekia, 2003; Arikan, 2009; Maennig & Ölschläger, 2011). However, little research deals with how the mediating structure emerges and coevolves with industries. Focusing on the characteristics of an open system, i.e. interdependence and dynamics, I contend that scientific collaboration, as a typical social interaction in scientific realms, can be a precursor of the technological systems. In other words, as social interactions through scientific collaboration (such as co-authorship or co-inventorship) are typified, various kinds of organizations or collectivities of social actors can appear, based on shared understandings of the scientific knowledge created through the scientific collaboration (e.g. Crane, 1972). These organizational forms, by recognizing interdependence among them, constitute a system with an epistemic boundary, which enables to facilitate the process of gradual stability of the social interactions.

To examine these arguments, I focus on emergence of a nanotechnology-based community in the U.S. between 1959 and 2004, and illustrate how nano-science-based knowledge is adopted by de novo dedicated nanotechnology start-ups, resulting in the emergence of a science-based community.

Organization of the Dissertation

This dissertation is organized as follows. First, I illustrate the relationship between scientific collaboration and the emergence/proliferation of technological systems for nanotechnology. Specifically, I measure characteristics of scientific collaboration in terms of intensity and heterogeneity by using nano-science-based articles. Since nanoscience is inherently inter-disciplinary, these characteristics are an important factor indicating how diverse relationships are constructed. Then, I estimate the rate of formation of technological systems with respect to intensity and heterogeneity of scientific collaboration. The notion of emergence is about whether and when a technological system emerges, which is specified into how the components and subsystems of technological systems (i.e. research competence, educational programs, industry-university centers, and technical knowledge) appear in a given region.

As the second stage of the analysis, I investigate the consequences of technological systems with respect to the community creation. Positing that the emergence of a community is driven by the formation of new organizations and populations, I test the relationships between the technological systems and the emergence of de novo firms dedicated to nanotechnology. Also, I consider the aspect that populations are diversified within a community. The emergence of de novo firms construct niches in existing populations and the niches can eventually become a new population dedicated to nanotechnology. The population diversification through the niche emergence is also an important indicator for the community creation. Thus, I examine how the nanotechnology-based populations are diversified depending on the proliferation of technological systems.

In addition, the role of technological systems in the emergence of a new community is further discussed by specifying the mechanisms of knowledge spillover. In prior literature, knowledge transposition between diverse social actors has been mainly studied in terms of knowledge spillovers. However, since the knowledge-spillover thesis does not explicitly explain its mechanism (e.g. Zucker, et al., 1998; Breschi & Lissoni, 2001a; 2001b), I focus on knowledge flow through tie formation as an alternative explanation for knowledge spillover. Accordingly, in the third analysis, the knowledge flow through tie formation is specified into knowledge streaking and knowledge leaking. By operationalizing knowledge streaking and knowledge leaking as collaboration and patent citation in creating patents respectively, I elaborate the mechanisms of knowledge spillovers. In this process, I argue, the presence of technological systems, especially instantiated by university-based research centers, can facilitate the knowledge flow.

Then, we will discuss the findings and their implications for the theoretical and practical purposes.

CHAPTER 2

SCIENTIFIC COLLABORATION AND EMERGENCE OF TECHNOLOGICAL SYSTEMS: THE CASE OF NANOTECHNOLOGY

ABSTRACT

In this study, I argue that scientific collaboration facilitates emergence of technological systems. Technological systems are defined as regional sources of knowledge and competence (i.e. the presence of local scientists, university educational programs, patents filed by regional organizations) that develop and diffuse technical and scientific knowledge in emerging fields of science. Scientific collaboration is defined as co-authorship based on new scientific or technical knowledge. I postulate that two dimensions of scientific collaboration, intensity and heterogeneity, will facilitate establishment of technological systems. These arguments are tested empirically in a new population of technological systems linked by nano-science and nanotechnology between 1959 and 2004. Findings support the arguments, and the role of scientific collaboration in the emergence of technological systems is discussed.

Keywords:

Technological system, scientific collaboration, nanotechnology

INTRODUCTION

This study seeks to understand how new scientific knowledge created by scientists from multiple organizations facilitates emergence of new social structures dedicated to the new knowledge. Within the social structures, referred to as "technological systems," activities to develop, disseminate, and utilize new knowledge are typified, which, in turn, derives economic consequences (i.e. innovation, entrepreneurship, or economic growth). Accordingly, these technological systems have been acknowledged as a salient platform to trace innovative activity (Oinas & Malecki, 2002; Moulaert & Sekia, 2003). In fact, the concept, technological systems, has been widely studied, typically in conjunction with variations on innovation, referred to variously as innovation systems (e.g. Moulaert & Sekia, 2003; Miyazaki & Islam, 2007; Oinas & Malecki, 2002), industrial clusters (Lorenzen & Maskell, 2004; Arikan, 2009), innovative milieux (Crevoisier & Maillat, 1991; Maennig & Ölschläger, 2011), industrial systems (Saxenian, 1994), and technological regimes (Nelson & Winter, 1982).

While many studies have paid attention to the outcomes of technological systems, the process by which these social structures emerge has been seldom studied. Because social structures are enacted by social actors (Giddens, 1984), understanding how technological systems are created can shed light on how innovation is created by social actors. From this standpoint, I focus on the emergence process of technological systems. Exploring the underlying mechanisms for emergence of technological systems, I attend to social actors who engage in the creation of new scientific knowledge with others who are both locally and distantly located. In particular, the collaboration for knowledge development is referred to as "scientific collaboration" (e.g. Crane, 1972; Moody, 2004; Zucker, Darby, & Brewer, 1998).

Given that collaboration, in general, has been understood as an important mechanism by which social ties for knowledge exchange are created (Bathelt et al., 2004; Owen-Smith & Powell, 2004), we can understand that scientific collaboration plays a crucial role in emergence of a technological system. The process is illustrated as follows: scientific collaboration creates a social structure among co-authors (and their affiliated organizations) through the creation of scientific articles (e.g. Ahuja, 2000; Powell et al., 2005; Singh & Fleming, 2010; Oliver, 2009). As new knowledge is channeled by scientific collaboration, social exchange between social actors can evolve into formal organizations or programs and departments within organizations. In these organizational forms, various feedback processes, like social learning and resource exchange, unfold. As a result, overarching structures are considered for knowledge creation, development, and reproduction, which can be realized as technological systems. In that as the collaborating practices are crystalized among social actors, technological systems can emerge, scientific collaboration is arguably a nucleus of a technological system.

To investigate the role of scientific collaboration in the emergence of technological systems, I address two dimensions of scientific collaboration: intensity and heterogeneity. Drawn from social network theory, the constructs of intensity and heterogeneity are understood in terms of how likely social ties to co-work for a new knowledge are made and how diverse those ties are. Specifically, intensity of scientific collaboration is defined as the likelihood that scientific publications created by multiple scientists appear in a region; the heterogeneity of scientific collaboration is defined as the extent to which diverse scientists are involved in a scientific publication. Furthermore, to specify the emergence of technological systems, technological systems are considered as a multi-layered structure composing of subsystems and components. In terms of knowledge development, diffusion, and utilization, four subsystems are identified: research competence, educational programs, industry-university centers, and technical knowledge. Acknowledging that specialized knowledge tends to be geographically localized (Breschi & Lissoni, 2001a & 2001b), I consider the geographical aspect in the construction of technological systems. Accordingly, technological systems are conceptualized, in this study, as regional sources of knowledge and competence (i.e. the presence of local scientists, university educational programs, patents filed by regional organizations) that develop and diffuse technical and scientific knowledge in emerging fields of science.

Based on the conceptualization of technological systems, four hypotheses are developed, which deal with the effects of scientific collaboration (i.e. intensity and heterogeneity) on the emergence of technological systems (i.e. subsystems and components). To examine the hypotheses, I consider the emergence of technological systems in the field of nanotechnology in the U.S. between 1959 and 2004. Specifically, the emergence rates of technological systems dedicated to nanotechnology in 182 regions in the U.S are investigated. Data are collected from multiple archival databases, including Nanobank, Nanotechnology-Now, the United States Patent and Trademark Office (USPTO), and Thomson ISI (formerly Institute for Scientific Information (ISI)), and based on the multi-sourced data, hypothesized variables are measured. Then, by using Cox proportional hazards models, emergence rates of technological systems are estimated with respect to the measures of scientific collaboration (i.e. intensity and heterogeneity). From the findings of the analyses, theoretical implications are discussed.

THEORETICAL BACKGROUND

Conceptualization of Technological Systems

In prior literature, technological systems are understood as ‘knowledge and competence networks supporting the development, diffusion, and utilization of technology in established or emerging fields of economic activity’ (Carlsson, 1997; p. 2). While technological systems have been variously defined as innovation systems (Moulaert & Sekia, 2003; Miyazaki & Islam, 2007; Oinas & Malecki, 2002), industrial clusters (Lorenzen & Maskell, 2004; Arikan, 2009), and technological regimes (Nelson & Winter, 1982), each conception includes a degree of interdependence between social actors (especially organizations) involved in innovation. That is, those studies viewed technological systems as networks among social actors around a technology. Yet, in terms of the interdependencies between system elements, the definition of technological systems varies in previous research. Podolny & Stuart (1995) reviewed the social constructionist view of technological systems: ‘the dense pattern of relations concatenating the innovations and associated actors’ (p. 1227). With the viewpoint, they conceptualized niche structures as ‘the number and the pattern of relations that connect the innovations in a niche’ (p. 1230). Barnett (1990) posits that organizations can be networked via systemic technology. Systemic technology refers to ‘multiple, interdependent components are linked via sophisticated interfaces to create the end-product’ (Rosenkopf & Tushman 1998; 323). Rosenkopf & Tushman (1998) illuminated the roles of cooperative technical organizations in technology development. A cooperative technical organization is defined as ‘a group that participates in technological information exchange, decision-making or standards-setting for a community’ (p. 315).

There are two definitions of interdependence in this context. First, the notion of interdependence is differentiated in terms of components of a technological system. Carlsson & Stankiwicz (1991) considered the system components as “agents”, indicating multi-level social entities, including firms, clusters, countries, etc. Some scholars have considered the components to be social actors (e.g. Podolny & Stuart, 1995; Barnett, 1990; Rosenkopf & Tushman, 1998), whereas others considered as impersonal entities, such as regulatory institutions (Van de Ven & Garud, 1989), or knowledge/competence (e.g. Carlsson & Jacosson, 1997). Second, the different notions of interdependence result from the recognition of different system boundaries. System boundaries indicate the range of system elements which the technological systems influence. Innovation systems (e.g. NISs or RISs, etc.) are confined to particular geographical boundaries (e.g. nations, regions, clusters, etc.). Some of technological systems have epistemic boundaries, especially based on technological configurations (Barnett, 1990) or cognitive aspects (Nelson & Winter, 1982).

In this sense, technological systems are not a simply physical collectivity of social actors, but they include all kinds of practices and logics that social actors can enact for technology development. Accordingly, in a technological system, subsystems are shown in various forms, such as the system’s knowledge, competence, or institutionalized roles. Carlsson & Jacobsson (1997) identified technological systems of factory automation in Sweden as economic competence (e.g. users and suppliers), institutional infrastructure (e.g. education and government policy), and the clustering of resources (e.g. supporting institutions and user-supplier linkages). Consistently, Jacobsson & Philipson (1997) explicated the technological systems in Sweden with higher education, economic competence, and government technology policy. These empirical cases show that technological systems include institutional forms, such as education, government activities, other institutions supporting certain technology, etc. That is, each subsystem has its own patterned activities in which social actors are involved. Specifically, subsystems are discerned with the activities to develop, diffuse, and utilize focal technology.

The interdependence among the subsystems is two-fold. The interdependence between the components of subsystems is understood as complementarity, defined as "the extent to which different human or material resources are needed as inputs, in addition to the intellectual resources of the scientist himself" (Bonaccorsi, 2008: p. 306). That is, complementarity is determined by epistemic needs of existing scientific realms. As diverse social actors are coordinated for the technological development, complementarity can be found in different types of subsystems, such as physical infrastructure, educational programs, research organizations, and government supports (e.g. Bonaccorsi, 2008). On the other hand, the interdependence among subsystems can be understood as integration. The subsystems, including impersonal entities, independently have their own activities. For example, technology creation is primarily governed by academic organizations (i.e. universities or research labs, etc.), whereas technology utilization is dominated by industrial organizations (e.g. incumbents, entrepreneurs, etc.). Still, those activities consistently help develop a common technology. This means that every subsystem plays certain roles for a certain technology and the roles of each subsystem are integrated within a certain boundary. That is, subsystems, which seemingly function independently, are indirectly coupled through a common technology.

To define the boundary of a technological system, this study attends to geographical locations of technological systems. In identifying technological systems, geographical aspects have been significantly considered, because knowledge tends to be geographically localized (Zucker, Darby, & Armstrong, 1998). Knowledge localization renders the distribution of technological systems geographically skewed. In particular, at the early stage of technology development, the skewed distribution of technological systems is amplified because critical resources for the development of new technology are available only in certain regions. Only social actors within these regions have access to resources to develop the technology, hence selective regions can have organizations involved in the early development of technology.

From this standpoint, I add the geographical aspect to the definition of technological systems, and accordingly, in this study, *technological systems are defined as regional sources of knowledge and competence (i.e. the presence of local scientists, university educational programs, patents filed by regional organizations) that develop and diffuse technical and scientific knowledge in emerging fields of science.*

Subsystems and Components

Following the definition of technological systems above, there are three activities in technological systems: development, diffusion and utilization. These activities are related to how social actors develop new technology or its applications. For example, research groups under the control of one faculty member or multiple faculty members are formed to create or develop new knowledge or technology – for example a research lab is established to develop the new knowledge. Knowledge diffusion is exemplified by the creation of educational programs for students, training programs for Ph.D. students, and the creation of university-industry research consortia. Joint activities between academia and industry can also facilitate knowledge diffusion. Last, the practical application of technical knowledge is an outcome of research. Patents or other institutional support for technology transfer (from the university to outside organizations, typically through licensing) are ways in which technology is utilized and applied.

Based on the development, diffusion and utilization of technology, technological systems can be said to have four subsystems: (1) research competence, (2) education programs, (3) industry-university centers, and (4) technical knowledge creation. *Research competence*, mainly engaged in technological development, is the foundation of scientific knowledge that provides technological opportunities. All the entities and practices regarding scientific research constitute research competence. For example, research groups, research labs or any types of collaborations within or between universities are components of the academic competence. *Educational programs* are any organization (or organizational forms) which deal with educational practices, such as degrees or departments in universities, including REU (Research Experience for Undergraduates). Through the educational programs, the ways to reproduce scientific knowledge are typified. The students from the educational programs can learn the specialized scientific knowledge and have capabilities to develop the knowledge for their own purpose. Consequently, educational programs expand the boundary of technological systems by attracting potential scientists to reproduce the knowledge.

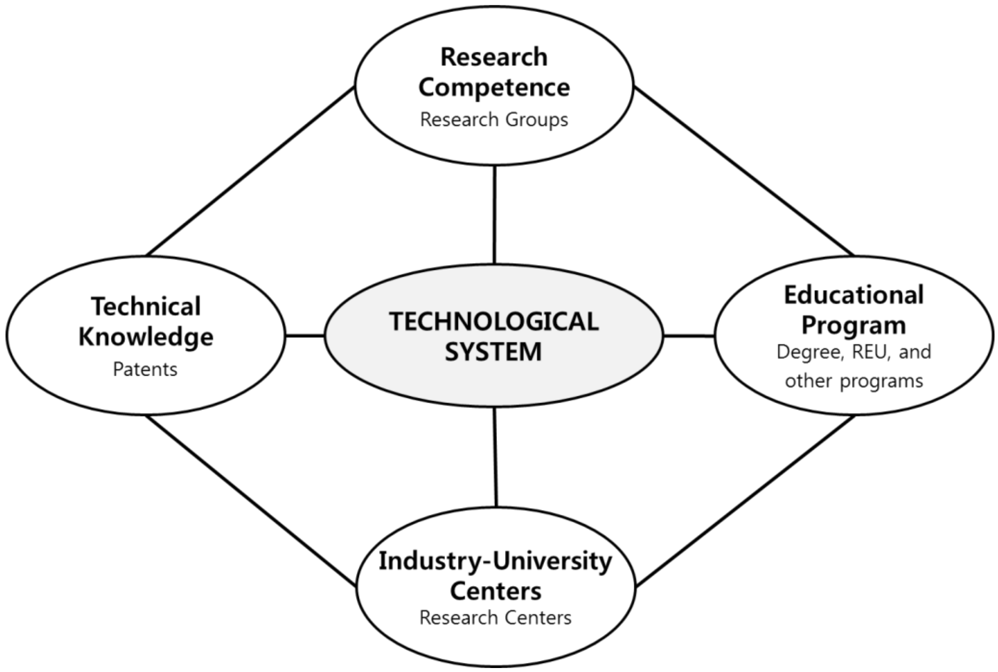
Industry-University Centers, as the ways to exchange the specialized scientific knowledge in the technological systems, are another subsystem of technological systems in terms of boundary spanning. As “bridges”, industry-university centers provide a place to exchange knowledge between universities and industries. Through industry-university centers, not only scientific knowledge can be transmitted to relevant industries, but also technological knowledge or resources from industries can flow into universities. For example, research centers, conferences, trade associations, or innovative milieu provide opportunities where diverse industrial populations, including academics, can be coordinated to seek for the further development of scientific knowledge. These industry-university centers also can be initiated by government or other non-profit organizations besides universities. For example, National Science Foundation (NSF) supports specific university-based research to create and develop specific knowledge. The governmental fundings can facilitate creating scientific knowledge, which is eventually expected to enhance economic development through technological innovation. Also, some non-profit organizations dedicated to the goals of advancing science and technology also provide grants to universities to facilitate development and utilization of particular technology, such as the Kavli Foundation, which has made grants to establish research institutes at some research universities to develop nanotechnology[2].

Technical knowledge refers to organizations by which scientific knowledge is commercially codified. Since the commercially-codified knowledge is inherently based on scientific knowledge, it can be a partial outcome of research competence. Yet, this doesn't mean that the products of research competence (i.e. scientific research) are automatically transitioned to the commercially-codified knowledge, because scientific research itself is not easy for industries to utilize. Scientific knowledge needs to be transformed to a certain knowledge which can be more easily commercialized. Patenting activities, as a representative way to utilize new knowledge, facilitate the transformation, so that they can provide business opportunities as well as technological opportunities. Accordingly, the subsystem of technical knowledge is composed of all the entities who own patents as the basis for commercialization.

Therefore, we can understand that technological systems are characterized with a multi-layered structure: multiple subsystems are integrated through certain technology, and their meanings or activities are implemented by their components. Figure 2-1 depicts the overview of a technological system.

[2] http://www.kavlifoundation.org/nanoscience

FIGURE 2-1: SUBSYSTEMS AND COMPONENTS OF TECHNOLOGICAL SYSTEMS



The Emergence of Technological Systems

Given that the components of a technological system are organizations or groups, the emergence of technological systems can be understood in conjunction with the emergence of new organizational forms. In particular, I focus on the emergence of communities. A community refers to a 'set of diverse, internally homogeneous populations which depend crucially on the nature of the technologies on which the populations are based' (Astley, 1985: p. 224). From the definition, we can understand that in terms of interdependence among organizations, the structure of technological systems can be analogous to that of a community. In fact, community ecology, which explores relationships between several populations and explains how a community emerges and evolves, assumes that a community is composed of organizations whose origin populations are heterogeneous and inter-related (Astley, 1985; Ruef, 2000). Furthermore, Astley (1985) emphasized a catalyst role of technologies in integrating diverse social actors (i.e. populations). Taken together, I posit that the process of community emergence can help specify how interdependence through a common technology can arise among diverse organizations. In other words, in terms that the existence of technology can render relationships among social actors (i.e. interdependence), the emergence of technological systems can be analogously understood with our knowledge concerning community emergence.

In prior literature, the community emergence has been studied within the context of the emergence of new organizations (Aldrich & Ruef, 2006; Astley, 1985; Ruef, 2000; Sorenson & Audia, 2005). These studies mainly deal with the roles of external environment in the emergence of new organizations. According to Stinchcombe (1965) and Romanelli (1991), organizations are influenced by conditions in their external environment at the time of founding. Based on this, ecological studies have considered the macro-structural characteristics of the external environment which influence the birth rates of new organizations (Hannan & Freeman, 1989). For example, Hannan & Freeman (1987) found that change in immigration can influence the birth rate of labor unions. Similarly, Zucker, Darby, and their colleagues have investigated how intellectual capital, such as scientific articles and patents, and human capital, such as star scientists, influence the creation of new organizations and new divisions of existing firms in the fields of biotechnology and nanotechnology (Zucker et al., 1998; Zucker et al., 2002; Darby & Zucker, 2006). These studies suggest that the formation of new organizations can be fueled by external factors and thus such environmental factors can be considered as important conditions in the emergence and evolution of new communities.

Meanwhile, scholars have also interests in the aspect that communities themselves also constitute elements of the environment and thus they enable organizations within the communities to interact with each other. Aldrich & Ruef (2006) argued that organizational communities themselves can set the context within which new populations emerge, because organizational communities reflect changes in societal norms and values, laws and regulations, and technological innovations. Related to this, Powell et al. (2005) illustrated the emergence and evolution of the life science field with the definition of the field as 'a community of organizations that engage in common activities and are subject to similar reputational and regulatory pressures' (p.1134), i.e. the life sciences. These studies imply that a new community can emerge as diverse organizations become connected to one another via a common knowledge (Powell et al., 2005; Astley, 1985) or collective identity[3] (Ruef, 2000; Wry et al., 2011). Hence, in this sense, community emergence has been understood as a product of inter-relationships across diverse populations (Astley, 1985; Ruef, 2000; Aldrich & Ruef, 2006).

From this literature on community emergence, we can understand the emergence of technological systems in two ways. First, environmental factors can facilitate creation of a technological system. Given that a technological system is constituted by organizations or groups involved in the development of a particular technology, the environmental factors correspond to the contexts where the technology is developed, such as knowledge stock (Zucker et al., 2007), institutional logic (Lounsbury et al., 2009), inventions of instrumentation (Darby & Zucker, 2006) or governmental support (Schoonhoven & Kim, 2012). In addition to the environmental factors, second, social actors themselves can actively influence the emergence of technological systems. In particular, social actors enact technological systems through creation

[3] In this sense, Ruef (2000) defined an organizational community as 'a bounded set of forms with related identities' (p. 658) where identity refers to 'the collective identity of a class of organizations' (p. 661).

of new organizational forms dedicated to the new technology. For example, research centers for nanotechnology are established to disseminate nanotechnology to industrial organizations in the region. In fact, it is typical that research centers are created by faculty members who collaborate in writing publications. Also, academic programs are created by scientists and faculty members who are actively involved in the development of nano-science. As these organizations are increasingly incorporated, technological systems can emerge.

HYPOTHESES

Intensity of Scientific Collaboration and Emergence of Technological Systems

From the concept of technological system, I acknowledge that technological systems are made up of crystallized relationships, which largely manifest as organizational forms, contributing to the process of technological development (e.g. Maennig & Ölschläger, 2011). This suggests that scientific collaboration, instantiated by co-authorship in scientific publications, can crystalize technological systems. Given that social networks play a role as a conduit for knowledge/resource exchange (Owen-Smith & Powell, 2004), social actors can exchange their knowledge through scientific collaboration (i.e. co-authorship). In particular, when social interaction through scientific collaboration intensifies, either by greater frequency or longer duration of interactions, relationships among co-authors can crystalize into the creation of organizational forms or structures which facilitate the collaboration further. In addition, as a product of scientific collaboration, publications convey a signal that new knowledge is legitimized among scientists, and thus based on the publications, further activities to develop, disseminate, and utilize the knowledge can be sought for (e.g. Zucker et al., 2007). Thus, the more intense interactions among scientists will yield the more scientific publications (i.e. the higher intensity of scientific collaboration), which, in turn, will facilitate creation of research groups, education programs, research centers or technical knowledge. As a result, these various subsystems established in a region will lead to emergence of a technological system.

This implies that technological systems can emerge when many social actors (i.e. scientists) come to exchange their own scientific knowledge and yield various scientific publications. Therefore, the intensity of scientific collaboration (i.e. the likelihood that scientific publications are created by multiple scientists in a region) can be arguably the basis for the emergence of technological systems, which is indicated by the emergence of subsystems and components. Thus, I hypothesize:

H_1: the more intense the scientific collaboration, the more likely the emergence of subsystems.

H_2: the more intense the scientific collaboration, the more likely the emergence of components.

Heterogeneity of Scientific Collaboration and Emergence of Technological Systems

Given that technological systems rely on interdependence among subsystems and components, next, I focus on how diverse social interactions emerge in scientific collaboration. To understand scientific collaboration, the conception of diversity among social actors matters. Since new knowledge is likely to be geographically localized, components of technological systems (i.e. organizations dedicated to the new knowledge) tend to emerge in the region where the knowledge is created. However, the components of technological systems can also emerge through scientific collaboration across regions. For example, Oinas & Malecki (2002) argued that the tendency to embrace new ideas at a focal region can be strengthened by interacting with diverse regions. Similarly, Bae et al. (2011) found that inter-firm relations that bind geographically remote and diverse sources of knowledge can facilitate new organizational forms (i.e. new firms in the U.S. biotech industry). Also, Simons & Robert (2008) analyzed the explosive transformation of the population of Israeli wineries between 1983 and 2004 and found that non-local wine industry experience prior to founding allowed new entrants to select the novel non-kosher form in the local population. From these studies, we can understand that by facilitating transferring a region's knowledge to another, scientific collaboration with others at a distance can lead to the establishment of components of technological systems.

Furthermore, diverse social actors collaborating for a scientific knowledge can differently maneuver the knowledge, because their attention to the development of the knowledge can be different. Some scientists tend to focus on advancing the knowledge; others pay more attention to dissemination of the knowledge. This will differentiate the ways to codify, coordinate and reproduce the knowledge for next research. As the ways to utilize the prior knowledge are differentiated by diverse scientists, the differentiated activities for the knowledge will facilitate establishment of various organizational forms. As evidence, Oinas & Malecki (2002) found that external relations (or collaboration across distant regions) help to sustain greater and more diversified technological capabilities within a region. The diversified technological capabilities can be represented by various organizational forms and thus these will lead to the emergence of new subsystems.

In this sense, we can understand that technological systems emerge as the differentiated activities of knowledge development are integrated. Given that the differentiated activities are driven by diverse scientists, heterogeneity of scientific collaboration (i.e. the extent to which diverse scientists are involved in a scientific publication) can have salient effects on emergence of both subsystems and components. Therefore, I hypothesize that the heterogeneity of scientific collaboration may enhance the likelihood that subsystems and components emerge:

H_3: The greater the heterogeneity of collaboration, the more likely the emergence of subsystems.

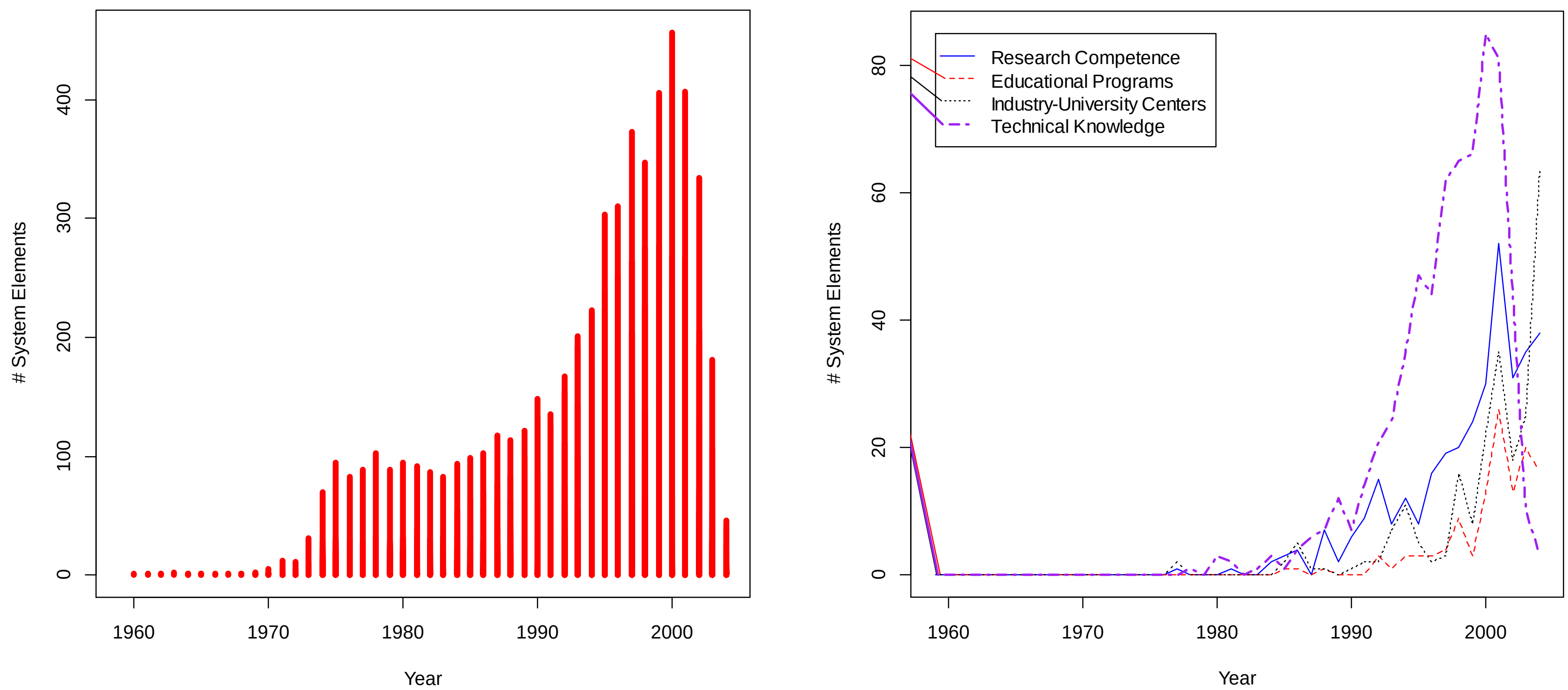
H_4: The greater the heterogeneity of collaboration, the more likely the emergence of components.

METHODS

Research Settings

To test the hypotheses, a field of nano- science and technology is considered. The field of nano- science and technology is a good setting to illustrate the role of scientific collaboration in the emergence of technological systems because, in that setting, we can clearly identify multiple organizations from diverse populations based on the same underlying knowledge. In fact, the nano- science and technology field includes organizations in both academia and industry, such as universities, research institutes, and companies, participating in development of nano-scale materials and products (Bonaccorsi & Vargas, 2010; Meyer & Persson, 1998; Selin, 2007). Accordingly, by looking at the field, we can specify the structure of technological systems rigorously. Figure 2-2 depicts the development of technological systems in the field of nanotechnology: Figure 2-2(a) represents the growth trend of the system elements between 1959 and 2004, while Figure 2-2(b) indicates the growth of system elements within each subsystem.

FIGURE 2-2: THE DEVELOPMENT OF THE TECHNOLOGICAL SYSTEMS IN NANOTECHNOLOGY, 1959-2004



(a) Total Number of Components by Year

(b) Annual Number of Components by Subsystem

The empirical tests of the hypotheses start with the geographic consideration of the technological systems. That is, the unit of analysis is a geographical location in the U.S., and indicated several ways, by county, by state, by a functional economic area or an MSA (metropolitan statistical area), for example. Building on Zucker et al. (2007) who considered "functional economic areas (i.e., central urban areas plus their suburbs and exurbs as "regions")" (p. 856), defined by the U.S. Bureau of Economic Analysis, as the units of analysis, I consider 182 functional economic areas (or BEAs) to investigate how U.S. regions have commercialized nanotechnology through technological systems over time. The time span of this study is between 1959 and 2004. The first date, 1959, is selected because Richard Feynman first articulated the idea of nanotechnology theoretically. The data collection stops in 2004, which the right truncation year.

Estimation Models

This study examines that the emergence of technological systems dedicated to nanotechnology is influenced by scientific collaboration. To test the hypotheses, the emergence of technological systems is estimated with respect to the intensity and heterogeneity of scientific collaboration. This study operationally assumes that the emergence of elements and subsystems is commonly followed by a Poisson process with the equation below:

$$\lambda_t = \lim_{\Delta t \to 0} \frac{P(t < T < t + \Delta t \mid T \geq t)}{\Delta t} \qquad (1)$$

Based on this, I adopt a Cox proportional hazards model to estimate the emergence rates of technological systems (i.e. elements and subsystems). The Cox proportional hazards model is useful to explicitly to test the time-dependent events (Amburgy & Carroll, 1986). Also, comparing to the parametric hazards models, which explicitly require a specified baseline model, the Cox proportional hazards models implicitly assume a base model. Thus, the latter is more flexible to build estimation models, and also helps prevent from making arbitrary assumptions about the baseline model. The estimation model is seen as follows:

$$\lambda_{it} = \lambda_{0t} \exp(X_{it-1}\tilde{\gamma} + \beta_1 INT_{it-1} + \beta_2 HET_{it-1}), \quad (2)$$

where $\boldsymbol{X}_{it-1}$ is a matrix of control variables in region i at time t-1; INT_{it-1} and HET_{it-1} denote intensity and heterogeneity of scientific collaboration in region i at time t-1 respectively; $\tilde{\gamma}$ is a vector of parameters for control variables and β_1 and β_2 indicate the parameters for the predictors; λ_0 corresponds to the baseline hazard function, which is left unspecified. To control the possible reverse causality, as indicated in the equation, I use one-year lagged values of the predictors and the control variables.

Measures

Dependent variables. The emergence of technological systems, as the dependent variable, is defined as the likelihood that subsystems and components of technological systems respectively appear at a given region in the U.S., and measured as binary codes between 1959 and 2004 to indicate the probability of the appearance of subsystems and components at a region respectively. Specifically each is coded 1 if subsystems or components of a technological system appear in a region at time *t*. Otherwise, they are coded 0. Since subsystems, by definition, are not physical entities, whether a subsystem appears is determined by the number of components. That is, assuming that a subsystem can be identified when two or more components show the meanings or activities of the subsystem, the appearance of subsystems is defined as the time period when two or more components within any subsystems are identified in a given region. Meanwhile, the appearance of components is identified when at least one component, regardless of subsystems, is observed in a given region.

As discussed, technological systems consist of four subsystems: research competence, educational programs, industry-university centers, and technical knowledge. Research competence is measured as the number of research groups of scientists who develop nano-science and technology. There are two kinds of research groups: explicit research groups and implicit research groups. While the explicit research groups have the term of "nanotechnology" in their group names or their mission statements explicitly, the implicit research groups are those who came from other scientific disciplines, such as material science, and began research in nanotechnology. Implicit research groups are counted as an element of research competence in a technological system when they published the first scientific article based on nano- science or nanotechnology. Research groups are listed from the directories of Nanotechnology-Now (http://www.nanotechnology-now.com) and the number of research groups in each region is annually traced between 1959 and 2004.

Second, education programs are those awarding academic degrees in nanotechnology or university-based Research Experience for Undergraduates programs (REUs) for nanotechnology. However, it is not possible to accurately identify when a department was formed. In this study, the number of departments is counted only when a university explicitly provides degree programs or courses in nanotechnology. Also, the establishment of REUs is traced over time to capture the educational programs. Given that universities inherently function to disseminate knowledge and educate students who are interested in the knowledge, the additionally specialized educational programs can indicate the commitment of a university to the activities for knowledge dissemination. Accordingly, the number of REUs in a region by year is considered to measure the education programs. The departments and REUs between 1959 and 2004 are listed from the directories of Nanotechnology-Now (http://www.nanotechnology-now.com).

The third component of technological systems is industry-university centers, defined as university-based organizational forms which function to facilitate the interactions between academia and industries. The component is typically represented by research centers embedded in universities. However, the name of "research center" is widely used in universities. Research groups established by faculty members also can be named as a "research center", which should be classified as an element of research competence. To differentiate from research competence, I consider only the research centers which have a function to bridge academia and industries as industry-university centers. Also, this subsystem includes government funded research centers and the research centers funded by private foundations, national labs, or state government[4], both of which are resided in a university. Thus, industry-university centers are listed from the directories of Nanotechnology-Now (http://www.nanotechnology-now.com) and measured as the number of the university-based research centers featured with industrial interactions, located in each region of the U.S. annually between 1959 and 2004.

Fourth, technical knowledge is measured as the organizations owning patents which are classified into nanotechnology. To identify the nanotechnology patents, I used the patents filed

[4] The former include Materials Research Science and Engineering Centers (MRSECs), National Nanotechnology Infrastructure network (NNIN), and Centers of Cancer Nanotechnology Excellences (CCNEs), to name a few. The latter is exemplified with Kavli foundation, Ames labs, and Calit2, to name a few

with the United States Patent and Trademark Office (USTPO). With the patent data, Zucker, Darby, & Fong (2011) identified nanotechnology-relevant patents, based on a "keyword" search.[5] Following their classification methods, the number of the nanotechnology-relevant patents applied is between 1959 and 2004 counted by region. For the geographical origins of the patents, I used the first inventors' address. Then, the number of organizations in which the patent authors are affiliated is counted by region and year, which constructs a measure of technical knowledge. To differentiate from research competence, universities are excluded from the technical knowledge subsystem.

Independent variables. There are two dimensions of scientific collaboration: intensity and heterogeneity. The intensity of scientific collaboration, defined as the likelihood that scientific publications created by multiple scientists appear in a region, is measured, based on the number of all co-authored scientific articles in nano- science and technology between 1959 and 2004. The "co-authored" scientific articles are identified if a published scientific article has two or more authors. To indicate the intensity of scientific collaboration in a region over time, I count the number of the co-authored scientific articles in a region by year.

The heterogeneity of scientific collaboration, defined as the extent to which diverse scientists are involved in a scientific collaboration, is measured as a 3-dimensional index to capture the extent to which scientists are co-located in a given space, such as a region, an organization, and a knowledge base. Adopting the conception of multi-dimensional distance, suggested by Knoben & Oerlemans (2006), the heterogeneity of scientific collaboration is

[5] The keywords used for the classification were "any term that was prefixed with "nano" and (A) the 140 most commonly occurring noun phrases in the *Virtual Journal of Nanoscale Science & Technology* (*VJN*), (B) 297 "glossary" terms primarily derived from recommended search lists received from collaborators and advisory board members who are specialists in the field and supplemented by a web search of nanotechnology glossaries, (C) with the exception of pure measurement terms". (Zucker et al., 2011: p. 5)

operationally defined as the extent to which the attributes of co-authors are geographically, organizationally, and technologically differentiated. Technically, the distance of scientific collaboration is computed, based on the attribute heterogeneity shown in each scientific article as:

$$d_{it} = \sum_{k=1}^{K} g_{itk} \cdot a_{itk} \cdot s_{itk}, \qquad (2)$$

where d_{it} denotes the distance among co-authors or co-inventors at region i at time t; g_{itk}, a_{itk}, and s_{itk} respectively indicate the k^{th} scientific publication's geographical, organizational, and technological heterogeneity at region i at time t. For the sake of heterogeneity, I counted the number of unique types of each attribute. For example, suppose that a scientific article is made by two authors, who are from the same location and affiliation, but different departments. Then, we can identify that in the article, there are one unique geographical attribute, one unique organizational attribute, and two unique technological attributes. Since the maximum possible attribute types are two (which is the case where the two co-authors have different attributes[6]), g_{itk} and a_{itk} are all 1/2; and s_{itk} is 1 (=2/2). With those, the distance of the scientific collaboration in the article is computed as 1/4 (=1/2*1/2*1). The distance of each scientific article is aggregated by region, which captures the heterogeneity of scientific collaboration in a region. The information on the geographical, organizational, and technological locations is indicated in each scientific publication, which is extracted from Thomson ISI (formerly Institute for Scientific Information) via Nanobank database (www.nanobank.org). For the geographical distance, I use the addresses of co-authors appearing in their scientific articles and see if the co-authors in each article are in the same region. For the organizational distance, the affiliations appearing in the

[6] The maximum possible number of attributes corresponds to the number of coauthors.

publication are compared. The technological distances are identified with the departments with which the authors are associated.

Control variables. To understand the effects of scientific collaboration on the emergence of technological systems, I control for the factors shown in prior research on the emergence of communities, which are discussed in the theoretical background section. In particular, I focus on the environmental factors, such as the universities, prior foundings of technological systems in neighbor regions, and index of the top 100 universities, research fundings, and nano-scientists.

First, the total number of universities located in the given region is counted between 1959 and 2004. Universities typically encourage the scientific research of faculty and their graduate students. As such, the more universities in a region, the more likely the emergence of technological systems in that region (e.g. Zucker et al., 1998; Aharonson, Baum, & Feldman, 2007). Even though these studies deal with the emergence of a new commercial field (i.e. firm formation), the logic that the resources from universities can be utilized by other social actors outside universities, arguably, can be still valid for the emergence of technological systems. The number of universities is collected from Carnegie Classification of Institutions of Higher Education (http://classifications.carnegiefoundation.org/). In this study, universities refer to four-year based universities in the U.S. According to the database, the universities are identified, based on the Integrated Postsecondary Education Data System (IPEDS).[7] Specifically, when an institute award bachelor's degrees, it is identified as a university. To distinguish two-year vs. four-year universities, entrance exam scores are considered.[8] With the list of universities obtained from the Carnegie Classification of Institutions of Higher Education, I trace the

[7] http://nces.ed.gov/ipeds/
[8] http://classifications.carnegiefoundation.org/methodology/ugrad_profile.php

presence of each university from its establishment date by year, and then count the number of universities which are present in a given year.

Applying the density dependence theory of organizational ecology, the size of technological systems established in a prior time period is controlled. This study mainly focuses on the early stage of the development of nano-science, so the instances of failures of the technological systems are empirically rarely found. Thus, instead of using density (the cumulative number of technological systems), using prior foundings (as the rate of change in density) is more helpful to predict the emergence of technological systems. I expect the typical inverted U-shaped relationships between prior foundings and emergence of technological systems. However, empirically, most components of technological systems come from universities. That is, the correlation between the prior founidngs of technological systems (typically measured with the number of the components) and the number of universities tends to be considerably high. From this standpoint, I use the number of universities as a proxy variable for the prior foundings of technological systems, and consider its square term to capture the density dependence.

The prior foundings of technological systems in neighbor regions are controlled to minimize the effect of spatial contagion (Greve, 2002; Cattani, Pennings, & Wezel, 2003). Spatial-contagion theory deals with "how geographically delineated subpopulations grow and interact with neighboring subpopulations" (Greve, 2002: 847). That is, in addition to the co-located social actors, the social actors located in neighboring regions also can influence the formation of technological systems as they can provide some resources for the development of nano-science or nanotechnology. Nearby regions are defined as the geographically adjacent regions of the focal region. To identify the nearby regions, I create an adjacency matrix which shows which regions share borders (e.g. Greve, 2002). With the adjacency matrix, the number of technological systems at a given region is counted and summed by year.

In addition, whether a given region has at least one of the top 100 universities in the U.S. is also considered a control variable. Most scientific achievement is led by top universities (Darby & Zucker, 2006). As a consequence, regions with at least one of the top 100 universities are more likely to contribute to the creation of new scientific knowledge. The presence of leading universities, thus, can facilitate the emergence of technological systems. Since nano-science is created from a nexus of multiple scientific fields, the indicator of top 100 universities is measured in respective scientific realms. In this study, the scientific realms are categorized according to the Zucker-Darby Science and Engineering (S&E) field categorization (Darby & Zucker, 1999): (1) biology/medicine/chemistry, (2) computer/information processing/multimedia, (3) integrated circuit/semi- & super-conductor, (4) other engineering, and (5) other sciences. Using the program rankings of each field, I first create 5 dummy variables for each region, indicating whether any of the top 100 universities in each of the fields are located in a given region. Then, the dummy variables are annually summed and divided by 5 (the number of categories) to be used as an index in the analysis. The index for top 100 universities, thus, ranges from 0 to 1.

Also, research fundings, i.e. grants, can be a source for technological systems. The projects granted by governmental institutions (e.g. NSF, NIH, etc.) or external organizations (e.g. national labs, or corporate funders) can be a trigger for attracting more scientists to involve the development of nano-science and nanotechnology, leading to the formation of a technological system. Following Darby & Zucker (2006), the research fundings of the top 100 universities in dollar values are used as a control variable.

The total population of nano-scientists at a region is also controlled. As a pool of human capital, scientists play an active role in initiating technological systems. This logic corresponds to the rationale that some studies on the emergence of organizational forms used the total number of relevant populations as a control variable (e.g. Stuart & Sorenson, 2003; Hedstrom, Sandell, & Stern, 2000; Zucker, et al., 1998; Calabrese, Baum, & Silverman, 2000). To identify nano-scientists, the number of Ph.D. graduates in nanotechnology from universities located in the given region is counted between 1959 and 2004. Specifically, to identify a Ph.D graduate specializing in nanotechnology, I identify whether his/her dissertation is concentrated on nanotechnology. By using ProQuest Dissertations & Theses Database[9], dissertations on nanotechnology between 1959 and 2004 are collected by using keyword search (e.g. nano*). Then, I count the number of the dissertations by region as a proxy variable for the number of nano-scientists. However, most scientists tend to be affiliated with at least one university, which can entail a collinearity issue as the number of universities is considered as a control variable. To reduce the bias from collinearity, I convert the count variable to a binary variable indicating whether a give region has two[10] or more nano-scientists at a given year.

Table 2-1 summarizes all measures: dependent, independent, and control variables described above. In Table 2-2, the descriptive statistics of the variables are specified.

[9] http://www.umi.com/en-US/products/dissertations/individuals.shtml
[10] The reference number of two is based on the condition for collaboration (or minimum number).

TABLE 2-1: CONCEPTS, DEFINITIONS, MEASURES, & DATA SOURCES

Construct	Definition	Measure	Data Source
DEPENDENT VARIABLES: Emergence of Technology Systems			
Emergence of Components:	The likelihood that components of technological systems appear at a given region in the U.S.	1 if one or more components within any subsystems of technological systems appear at a region in the U.S. at time *t* 0 else	Directories of Nanotechnology-Now (www.nanotechnology-now.com)
The Emergence of Subsystems	The likelihood that subsystems of the technological system appear at a given region	1 if a new subsystem of technological systems appear at a region in the U.S at time *t* 0 else	Directories of Nanotechnology-Now (www.nanotechnology-now.com)
• Emergence of Research Competence	The likelihood that organizations other than universities support nanotechnology development in a given U.S. region.	1 if one or more components of research competence (i.e. research groups, laboratories, and facilities) appear, given the research-competence subsystem doesn't preexist, at a region in the U.S. at time *t* 0 else	Directories of Nanotechnology-Now (www.nanotechnology-now.com)
• Emergence of Educational Programs	The likelihood that nanotechnology education is initiated in a given U.S. region	1 if one or more nanotechnology-specialized educational programs appear, given the educational-program subsystem doesn't preexist, at a region in the U.S. at time *t* 0 else	Directories of Nanotechnology-Now (www.nanotechnology-now.com)
• Emergence of Industry-University Centers	The likelihood that university-industry relations for nanotechnology development are formalized in the U.S. region	1 if one or more nanotechnology-specialized organizational forms functioning fostering industrial relations (e.g. research centers, or forums, etc.) appear, given the industry-university center subsystem doesn't preexist, at a region in the U.S. at time *t* 0 else	Directories of Nanotechnology-Now (www.nanotechnology-now.com)
• Emergence of Technical Knowledge	The likelihood that the knowledge on nanotechnology is officially codified in the U.S. region.	1 if one or more organizations file a patent dedicated to nanotechnology, given the technical-knowledge subsystem doesn't preexist, at a region in the U.S. at time *t* 0 else	Nanobank, 1959—2004 USPTO
INDEPENDENT VARIABLES: Scientific Collaboration			
Intensity of Scientific Collaboration	The likelihood that scientific publications created by multiple scientists appear in the U.S. region	The total number of nano-science-related articles which are created by two or more authors at a region in the U.S. at time t.	Nanobank, 1959—2004 Thompson ISI

Heterogeneity of Scientific Collaboration	The extent to which diverse scientists are involved in a scientific publication	$d_{it} = \sum_{k=1}^{K} g_{itk} \cdot a_{itk} \cdot s_{itk}$ d_{it}: heterogeneity among co-authors at region *i* at time *t* g_{itk}: k^{th} scientific publication's geographical heterogeneity at region *i* at time *t* (The proportion of articles where co-authors are located in different regions) a_{itk}: k^{th} scientific publication's organizational heterogeneity at region *i* at time *t*. (The proportion of articles where co-authors are affiliated in different organizations) s_{itk} : k^{th} scientific publication's technological heterogeneity at region *i* at time *t*. (The proportion of articles where co-authors are located in different scientific realms)	Nanobank, 1959-2004 Thompson ISI
CONTROL VARIABLES			
Total Number of Universities	Total Number of Universities	The number of research universities located in a region in the U.S. at time t	Carnegie Classification of Institutions of Higher Education, 1959-2004
Prior foundings of Technological Systems in Neighbor Regions	The rate of change in the cumulative number of technological systems at neighbor regions	The average number of elements of technological systems appearing at the neighbor regions at time *t-1* * neighbor regions: the areas which share boundaries of the focal region	Directories of Nanotechnology-Now (www.nanotechnology-now.com)
Index of Top 100 Universities	Whether top 100 universities in S&E field categorization (Zucker & Darby, 1999) are located in a given region	Whether the mean value of 5 dummy variables indicating whether any of top 100 universities in 5 S&E fields are located in a region in the U.S. is greater than 0.9	US-News Rankings, 1959-2004
Research Fundings	Financial support for the development of nano-science	Total dollar values of research fundings granted by governmental institutions (e.g. NSF, NIH, etc.) or external organizations (e.g. national labs, or corporate funders) in a region in a U.S. at time t	NSF: Funding, 1959-2004
Indicator of Nano-Scientists	Whether a given region bears human capital for Nanotechnology development	Coded 1 if two or more Ph.D. graduate whose dissertation topics are involved in nano-science in a region in the U.S. at time t Or 0 if else	ProQuest Dissertations & Theses Database & Nanobank, 1959-2004

TABLE 2-2: DESCRIPTIVE STATISTICS

N=8372	Mean	SD	Min	Max	1	2	3	4	5	6	7	8	9	10	11	12
1. # Subsystems	0.28	0.81	0	4												
2. # Components	4.22	20.21	0	457	0.49											
3. Research Competence Subsystem	0.04	0.29	0	9	0.51	0.44										
4. Educational Program Subsystem	0.01	0.14	0	4	0.41	0.27	0.65									
5. Industry-University Center Subsystem	0.03	0.29	0	14	0.39	0.25	0.70	0.62								
6. Technical Knowledge Subsystem	0.04	0.19	0	1	0.50	0.54	0.30	0.20	0.16							
7. Intensity of Scientific Collaboration	0.07	0.15	0	1	0.29	0.13	0.12	0.10	0.10	0.14						
8. Heterogeneity of Scientific Collaboration	16.95	81.65	0	1399	0.63	0.73	0.59	0.43	0.47	0.48	0.19					
9. Total # University	6.40	9.83	0	96	0.35	0.57	0.31	0.19	0.20	0.34	0.18	0.46				
10. Prior Foundings in Neighbor Regions	1.32	3.88	0	60	0.51	0.21	0.26	0.24	0.22	0.21	0.31	0.41	0.13			
11. Index of Top 100 Ranked University	0.52	0.50	0	1	0.27	0.18	0.13	0.09	0.09	0.16	0.18	0.18	0.36	0.08		
12. Research Funding (dollars in thousands)	11.79	54.46	0	3637.58	0.25	0.06	0.09	0.07	0.07	0.10	0.20	0.14	0.04	0.22	0.07	
13. Nano-scientists	0.17	0.38	0	1	0.58	0.36	0.29	0.20	0.19	0.34	0.34	0.40	0.35	0.32	0.40	0.24

RESULTS

Hypothesis Tests

Table 2-3 presents the effect of scientific collaboration (i.e. intensity and heterogeneity) on the emergence of technological systems (i.e. subsystems and components). Specifically, the coefficients in the Cox proportional hazards models indicate the relations between the technological-system emergence rate and the intensity and heterogeneity of scientific collaboration. The greater the coefficients are, the more likely the emergence of subsystems or components. In Table 2-3, Models 1 through 4 present the emergence rates of the subsystems of technological systems, estimated with respect to the intensity and heterogeneity of scientific collaboration. Models 5 through 8 report the estimates of the emergence rate of components of technological systems.

For the emergence of the subsystems, the estimates reveal that both intensity and heterogeneity of scientific collaboration increase the speed of the emergence of the subsystems. Specifically, in Model 4, we can find that the estimated hazard ratios are 1.014 ($=e^{.013}$) and 2.924 ($=e^{1.073}$) respectively, which denote the multipliers which raise the emergence rates when one unit of each predictor increases. That is, when the intensity and heterogeneity of scientific collaboration increase by one unit, the emergence rates of the subsystems are 1.014 and 2.924 times greater than the base rate respectively.

TABLE 2-3: COX PROPORTIONAL HAZARD MODELS PREDICTING THE EMERGENCE OF TECHNOLOGICAL SYSTEMS WITH RESPECT TO SCIENTIFIC COLLABORATION

	Emergence of Subsystems				Emergence of Components			
	Model 1	**Model 2**	**Model 3**	**Model 4**	**Model 5**	**Model 6**	**Model 7**	**Model 8**
CONTROLS								
Total # Universities	.148*** (.027)	.144*** (.026)	.144*** (.028)	.140*** (.026)	.116*** (.021)	.092*** (.025)	.116*** (.021)	.091*** (.025)
Total # Universities^2	-.001** (.000)	-.001** (.000)	-.001** (.000)	-.001** (.000)	-.001*** (.000)	-.001*** (.000)	-.001*** (.000)	-.001*** (.000)
Prior Foundings in Neighbor Regions	.053 (.037)	.047 (.037)	.052 (.037)	.047 (.036)	.114 (.071)	.100 (.071)	.114 (.071)	.100 (.071)
Prior Foundings in Neighbor Regions^2	-.000 (.001)	.000 (.001)	-.001 (.002)	-.000 (.001)	-.003 (.003)	-.002 (.003)	-.003 (.003)	-.002 (003)
Index of Top 100 Ranked University	1.439** (.529)	1.075† (.628)	1.360** (.524)	1.006 (.622)	.943 (.668)	.663 (.713)	.933* (.672)	.640 (.719)
Research Funding (dollars in thousands)	.001 (.001)	.001† (.001)	.001 (.001)	.001 (.001)	.000 (.001)	.000 (.001)	.000 (.001)	.000 (.001)
Nano-scientists (0/1)	1.352*** (.276)	1.073*** (.288)	1.346*** (.273)	1.077*** (.285)	2.355*** (.414)	2.192*** (.434)	2.353*** (.412)	2.185*** (.430)
HYPOTHESIZED EFFECTS								
Intensity of Scientific Collaboration		.014*** (.004)		.014*** (.004)		.005* (.002)		.005* (.002)
Heterogeneity of Scientific Collaboration			1.028* (.423)	1.073* (.461)			.518 (.825)	.852 (.770)
Log Likelihood	-423.03	-416.06	-421.43	-414.50	-180.51	-178.58	-180.46	-178.44
AIC	860.06	848.13	858.85	847.01	375.02	373.15	376.92	374.88
ΔDeviance (χ^2)	-	13.93***	3.21†	17.06***	-	3.87*	.10	4.15
N (obs)	7315	7315	7315	7315	8029	8029	8029	8029
# BEAs	182	182	182	182	182	182	182	182

† p <.1, * p <.05, ** p <.01, *** p <.001

Accordingly, we find that scientific collaboration (i.e. intensity and heterogeneity) plays a critical role in facilitating the emergence of subsystems. In particular, given that the emergence of new subsystems signifies that the ways to develop nanotechnology are diversified, we can understand that the diverse social ties drawn from the heterogeneity of scientific collaboration are related to the differentiation of the activities for knowledge development.

In Model 8, the relationships between scientific collaboration and the emergence of components of technological systems are tested. The results reveal that the intensity of scientific collaboration is positively related to the emergence rate of the components of technological systems (β = .005; $p < .01$). The estimated hazard ratio is 1.005 (=$e^{.005}$). That is, when the intensity of scientific collaboration increases by one unit, the emergence rate of the components is 1.005 times greater than the base rate. This finding interprets that as the number of scientific collaboration increases (or the knowledge related to nanotechnology is accumulated through scientific collaboration), the number of organizational forms dedicated to nanotechnology correspondingly increases. In contrast, the effect of heterogeneity of scientific collaboration on the emergence of the components of technological systems is not significant.

To specify the emergence of technological systems, I additionally examine how scientific collaboration can facilitate the emergence rate of components within each subsystem. The emergence of components in each subsystem is identified when the first component of the subsystem is established. Based on the "first-establishment" event, the emergence rate of components within each subsystem is estimated with respect to the intensity and the heterogeneity of scientific collaboration by using the Cox proportional hazards model (Table 2-4). In Table 2-4, Models 1 through 4, Models 5 through 8, Models 9 through 12, and Models 13 through16 respectively present the estimations of the research-competence emergence, the educational-program emergence, the industry-university-center emergence, and technical-knowledge emergence.

TABLE 2-4: COX PROPORTIONAL HAZARD MODELS PREDICTING THE EMERGENCE OF SUBSYSTEMS IN TECHNOLOGICAL SYSTEMS WITH RESPECT TO SCIENTIFIC COLLABORATION

	Emergence of Research Competence				**Emergence of Educational Programs**			
	Model 1	**Model 2**	**Model 3**	**Model 4**	**Model 5**	**Model 6**	**Model 7**	**Model 8**
CONTROLS								
Total # Universities	.097*** (.021)	.088*** (.022)	.096*** (.021)	.087*** (.023)	.060** (.021)	.071** (.025)	.060** (.021)	.070** (.025)
Total # Universities^2	-.001*** (.000)	-.001*** (.000)	-.001*** (.000)	-.001*** (.000)	-.000* (.000)	-.000* (.000)	-.000* (.000)	-.000* (.000)
Prior Foundings in Neighbor Regions	.180** (.061)	.163** (.058)	.180** (.061)	.163** (.059)	.097† (.054)	.104† (.054)	.098† (.053)	.105† (.054)
Prior Foundings in Neighbor Regions^2	-.006† (.003)	-.005† (.003)	-.006† (.003)	-.005† (.003)	-.002 (.002)	-.002 (.002)	-.002 (.002)	-.002 (.002)
Index of Top 100 Ranked University	.371*** (.661)	.180*** (.729)	.354*** (.663)	.155*** (.730)	1.013 (.798)	1.099 (.798)	1.007 (.800)	1.088 (.802)
Research Funding (dollars in thousands)	.000 (.000)	.000 (.001)	.000 (.001)	.000 (.001)	-.000 (.000)	-.000 (.000)	-.000 (.000)	-.000 (.000)
Nano-scientists (0/1)	2.061*** (.297)	1.913*** (.320)	2.056*** (.295)	1.902*** (.317)	2.048*** (.414)	2.043*** (.414)	2.044*** (.414)	2.040*** (.414)
HYPOTHESIZED EFFECTS								
Intensity of Scientific Collaboration		.005* (.002)		.005* (.002)		-.001 (.001)		-.000 (.001)
Heterogeneity of Scientific Collaboration			.341 (.559)	.471 (.554)			.727 (.740)	.671 (.772)
Log Likelihood	-545.46	-544.00	-265.66	-545.77	-210.60	-210.40	-210.43	-210.26
AIC	265.73	264.00	547.33	263.88	435.20	436.81	436.86	438.52
ΔDeviance (χ^2)	-	3.45†	.13	3.69	-	.39	.34	.68
N (obs)	7780	7780	7780	7780	8097	8097	8097	8097
# BEAs	182	182	182	182	182	182	182	182

† p <.1, * p <.05, ** p <.01, *** p <.001

TABLE 2-4 (CONT'D): COX PROPORTIONAL HAZARD MODELS PREDICTING THE EMERGENCE OF SUBSYSTEMS IN TECHNOLOGICAL SYSTEMS WITH RESPECT TO SCIENTIFIC COLLABORATION

	Emergence of Industry-University Centers				**Emergence of Technical Knowledge**			
	Model 9	**Model 10**	**Model 11**	**Model 12**	**Model 13**	**Model 14**	**Model 15**	**Model 16**
CONTROLS								
Total # Universities	.112*** (.026)	.096*** (.029)	.111*** (.026)	.093** (.029)	.152** (.048)	.150** (.048)	.150** (.048)	.147** (.047)
Total # Universities^2	-.001*** (.000)	-.001*** (.000)	-.001*** (.000)	-.001*** (.000)	-.001 (.001)	-.001 (.001)	-.001 (.001)	-.001 (.001)
Prior Foundings in Neighbor Regions	.045 (.061)	.033 (.063)	.047 (.061)	.035 (.063)	.035 (.056)	.026 (.059)	.034 (.055)	.021 (.059)
Prior Foundings in Neighbor Regions^2	-.001 (.002)	-.001 (.002)	-.002 (.002)	-.001 (002)	.001 (.002)	.001 (.003)	.000 (.002)	.001 (.003)
Index of Top 100 Ranked University	.765 (.654)	.481 (.696)	.759 (.656)	.459 (.699)	.763 (.638)	.656 (.710)	.765 (.627)	.619*** (.701)
Research Funding (dollars in thousands)	-.001 (.001)	-.001 (.001)	-.001 (.001)	-.001 (.001)	.004* (.002)	.004* (.002)	.003† (.002)	.003† (.002)
Nano-scientists (0/1)	1.876*** (.417)	1.725*** (.445)	1.866*** (.412)	1.707*** (.437)	.966** (.312)	.880* (.350)	.955** (.313)	.843* (.355)
HYPOTHESIZED EFFECTS								
Intensity of Scientific Collaboration		.004* (.002)		.004* (.002)		.002 (.003)		.003 (.003)
Heterogeneity of Scientific Collaboration			.943 (.611)	1.176* (.582)			.983† (.576)	1.089† (.564)
Log Likelihood	-213.27	-211.32	-212.94	-210.80	-363.75	-363.50	-362.63	-362.17
AIC	433.28	431.65	434.58	432.57	741.51	742.99	741.27	742.34
ΔDeviance (χ^2)	-	3.90*	.66	4.95†	-	.51	2.24	3.16
N (obs)	8001	8001	8001	8001	7554	7554	7554	7554
# BEAs	182	182	182	182	182	182	182	182

† *p* <.1, * *p* <.05, ** *p* <.01, *** *p* <.001

Overall, we find differentiated effects of scientific collaboration on the emergence rates of subsystems. On one hand, the intensity of scientific collaboration helps speed attainment of research competence emergence (β = .005; p < .05) and industry-university center emergence (β = .004; p < .05). Since the intensity of scientific collaboration implies that the given region has the increasing number of social actors who accept the ideas of nano-science, its significant effect on the emergence of research competence indicates that scientific collaboration can crystalize organizational forms for research. The research aspects in technological systems also can be implemented through industrial relations. While research competence captures the ability to develop nano- science and technology within academia, the industry-university centers signify the possibility of knowledge exchange with industrial organizations. Accordingly, as the knowledge on nano-science is accumulated with the increase in scientific collaboration, the incorporation of the industry-university can be facilitated to commercially utilize the scientific knowledge.

On the other hand, we find that the heterogeneity speeds up the emergence of industry-university centers ($\beta = 1.176$; $p < .05$) and technical knowledge ($\beta = .983$; $p < .1$). In terms that industry-university centers and technical knowledge inherently concern coalition among social actors, this finding reveals that diverse social actors in knowledge creation (i.e. the higher level of heterogeneous scientific collaboration) are likely to form certain organizations to take the boundary-spanning advantages. As discussed, the industry-university centers signify industrial relations, and patenting activities seek for business opportunity based on scientific knowledge. Both activities from the subsystems indicate that industrial organizations can engage in the utilization of new scientific knowledge. Thus, these findings reveal that diverse collaborators to create a scientific knowledge can expand the boundary of technological systems by including industrial organizations (e.g. Kogut, Walker, & Kim, 1995).

DISCUSSION AND CONCLUSION

In this study, I find that scientific collaboration plays a role in the emergence of technological systems in the field of nano- science and technology and further, the dimensions of scientific collaboration (i.e. intensity and heterogeneity) have differentiated effects on the emergence of the technological systems. The intensity of scientific collaboration is positively related to the emergence of subsystems and components in technological systems, whereas the heterogeneity of scientific collaboration is positively related to only the emergence of subsystems. When the subsystems are specified, the intensity of scientific collaboration has significant effects on the emergence of research competence and industry-university centers. On the other hand, the heterogeneity of scientific collaboration is significantly related to the emergence of industry-university centers and technical knowledge. These results demonstrate that the social ties constructed through scientific collaboration can be crystalized in certain organizational forms and in this process the characteristics of scientific collaboration (i.e. intensity and heterogeneity) differentiate technological systems.

Of the findings, the effect of the heterogeneity of scientific collaboration on the emergence of technological systems can be further understood with two network concepts: closure and brokerage. Closure is about the "benefits of protection from variation in opinion and behavior, protection provided by focusing on connections with ego's own kind" (Burt, 2010: p. 4). Thus, through closure, social actors can demarcate their boundaries of social relationships. In their networks, social actors can deepen their knowledge and build trust among those who are connected within the "shared" boundary. As a result, closure elicits enhanced collaboration, leading to organizational forms. In contrast, brokerage is about the "benefits of exposure to variation in opinion and behavior provided by building connections across structural holes" (Burt, 2010: p. 4). Thus, brokerage indicates the broader opportunities to have diverse ideas and practices. The broader opportunities provide advantages in detecting and developing productive ways of looking at problems. This enables social actors to create various types of organizational forms characterized with different functions.

From this juxtaposition, it can be understood that the insignificant effect of heterogeneity of scientific collaboration on the emergence of system elements (Table 3) reflects the mixed effect of brokerage. The diverse ideas elicited by brokerage can help explore new ways to advance the ideas and thus new organizational forms representing the diverse activities can be established. However, the diverse ideas may not be coherent or can entail conflict among social actors, demotivating forming organizations. Since the social ties from the greater heterogeneity of scientific collaboration can have more structural holes, the heterogeneity of scientific collaboration is more closely related to brokerage rather than closure. Therefore, the heterogeneity of scientific collaboration can indicate both benefits and disadvantages of brokerage in forming organizations.

Based on the findings, this study has two theoretical implications. First, technological systems analogously attest the theory of community creation (Aldrich & Ruef, 2006; Astely, 1985). It has been widely discussed that a new community can be created when diverse, multiple organizations are involved in developing common knowledge (e.g. Aldrich & Ruef, 2006; Ruef, 2000; Astley, 1985), and knowledge sharing among diverse social actors is facilitated by social ties (e.g. Powell et al., 2005). This study elaborates the knowledge on community creation by maintaining that the creation of social structure around new knowledge (i.e. scientific collaboration) can be a precursor of technological systems. That is, I illuminate the aspect that new organizational forms can be crystalized by prior relational structure. Since organizational communities characterize interdependence of diverse populations, the crystallization process from relational structure to organizational forms can be concerned with the emergence of organizational communities. Specifically, the finding in this study, the relations between scientific collaboration and the emergence of technological systems, can comprehensively explain how inter-relationships between heterogeneous organizations within an organizational community can be constructed.

Second, the notion of scientific collaboration can be juxtaposed with the concept of knowledge spillovers. The knowledge spillovers, originally treated as inter-firm influence of R&D spending in firm productivity, indicate that the knowledge created in universities can be transported to commercial organizations (i.e. firms) (Griliches, 1979; Jaffe, 1989). Broadly, knowledge spillovers have been understood as phenomena where knowledge transfer comes to appear from one area which owns the knowledge (i.e. academia) to the other area which doesn't (i.e. industries). Related to this, Zucker et al. (1998) defined knowledge spillovers as 'positive externalities of scientific discoveries on the productivity of firms which neither made the discovery themselves nor licensed its use from the holder of intellectual property rights' (p. 65).

While many scholars have been interested in the knowledge spillover phenomena, the studies leave some issues to be further considered (Breschi & Lissoni, 2001a & 2001b): (1) knowledge spillovers are not actually tested, (2) the knowledge the universities actually provide to industries may not be the very knowledge the universities create, and (3) social actors intend to make coalition to create knowledge, so that the "transporting" phenomena of knowledge is not confined to only localized knowledge spillovers. This study delves into the third issue. As discussed, scientific collaboration can be made across regions, organizations, or scientific realms; and particularly the social ties which stem from scientific collaboration crystalize a multi-layered structure, i.e. technological systems. This emphasizes the aspect that social actors actively enact their social structure. In this sense, the findings in this study suggest that the "transporting" phenomena (i.e. knowledge spillover) are neither epiphenomenal nor externalities, but intended by scientists. Therefore, the notion of scientific collaboration can provide a different lens to knowledge spillovers.

While this study provides some implications, it has also some challenges to be improved. First, the heterogeneity of scientific collaboration could be more elaborated by directly measuring the network features of scientific collaboration. In this study, the heterogeneity is considered in terms of whether collaborators are co-located in a certain category (i.e. geographical locations, organizations, or scientific realms). As a type of network structure, scientific collaboration can reflect various structural features, which can help specify the role of scientific collaboration in the emergence of technological systems. Second, the emergence of technological systems is examined, based on the emergence of new organizational forms (such as subsystems or components). As defined as a regional network, technological systems also can be considered as a network structure composing of various system components. Since the interdependence among the components can be differentiated by region, if the structure of technological systems can be specified, how technological systems can be differently composed in different regions. Furthermore, this will help understand the evolution of technological systems. Last, the role of government could be theorized. As socio-political legitimacy (Aldrich & Ruef, 2006), the governmental attention to nanotechnology also influence the emergence of technological systems in the field. In this study, the government-funded research centers can be interpreted as a part of initiatives from government, but the governmental role for the emergence of technological systems could be further investigated.

In sum, by emphasizing technological systems as an embodiment of community creation, this study unpacks the underspecified mechanisms of the emergence of technological systems. Technological systems provide not only an alternative mechanism for community creation, but also an opportunity to integrate fragmented theories from different disciplines to capture the conjecture that collaboration can lead to new organizational forms. By considering different explanations for the mechanisms of emergent phenomena, such as social movements, innovation diffusion, and entrepreneurship, the emergence process of technological systems can be further specified.

CHAPTER 3

THE ROLE OF TECHNOLOGICAL SYSTEMS IN CREATION OF A NANOTECHNOLOGY COMMUNITY

ABSTRACT

This study investigates how new science-based knowledge is adopted by de novo dedicated nanotechnology start-ups, resulting in the eventual creation of a science-based community. I argue that technological systems play a significant role in the process of community creation. By dispersing relevant scientific knowledge across multiple social actors, technological systems enhance the likelihood that new science and novel technology attract diverse social actors (including entrepreneurs) to apply the technology to new business opportunities. As a result, many organizations originating in separate existing populations increasingly become involved in developing and commercializing a new technology, which over time, creates the nucleus for creation of a new science-based community.

Keywords:

Technological system, community creation, nanotechnology

INTRODUCTION

This study seeks to understand how new knowledge creates conditions for emergence of a community around new technology. To explain community creation, prior literature has focused on the processes of legitimation (e.g. Aldrich & Ruef, 2006). Aldrich & Ruef (2006) argued that legitimation deals with social actors' collective behavior around community creation (p. 258). Through collective action, entrepreneurs (or innovators) can frame what they do to make their activities taken for granted - cognitive legitimacy[11]. In this sense, legitimacy is understood as the congruence between individual perception and an environmental element and as a result of the congruence, social actors take the environmental element for granted, leading to more social actors to adopt the knowledge (Oliver, 1990). Oliver (1990) argued that organizations, which use inter-organizational relationships to achieve legitimacy, do so to "demonstrate or improve its reputation, image, prestige, or congruence with prevailing norms in its institutional environment" (p. 246).

This implies that inter-organizational relationships created to build organizational legitimacy can be an element in the community creation process. According to Aldrich & Ruef (2006), new organizations, at first, achieve legitimacy in their own right, and then attempt to establish standards by collaborating with other organizations or populations. Those activities are assisted by institutional actors, such as government, educational organizations, and the media which create regulations and resources relevant to the new technology (Aldrich & Ruef, 2006: p. 258). This process suggests that social actors utilize strategies to facilitate relations between

[11] Aldrich & Ruef (2006) defined cognitive legitimacy as 'the acceptance of a new kind of venture as a taken for granted feature of the environment' (p. 186).

diverse organizational entities, which eventually result in community creation through gaining legitimacy.

However, the legitimation thesis is not a sufficient condition to explain the creation of a community if the community is based on specialized knowledge (i.e. science and technology). As Astley (1985) argued, a common technology (or knowledge, more generally) plays a critical role in the process of integrating heterogeneous social actors into a common community. Yet, specialized knowledge tends to be localized and thus the knowledge is more difficult to understand and apply by those not involved in its development (Jaffe, Trajtenberg & Henderson, 1993; Zucker, Darby, Armstrong, 1998). This suggests that as new knowledge is specialized and localized, it will be difficult to acquire and imitate at a distance (Breschi & Lissoni, 2001a). It is likely that localized knowledge will reside within relatively homogenous organizations and populations which can understand and apply the knowledge. Given that a homogenous population does not constitute a community (Astley, 1985), to explain the process of community emergence, additional efforts to achieve the community-based legitimacy are inevitable.

When we consider the character of new knowledge, to understand the creation of a new organizational community, it is necessary to determine how the specialized (and thus possibly fragmented) knowledge can be integrated. The owners of new knowledge owners often seek to acquiring and imitating it (see Romer, 1990: p. s74), which prevents diverse social actors from adopting new knowledge and also discourages the integration of knowledge by diverse social actors. Zucker, Darby, & Brewer (1998) found that social actors involved in biotechnology (such as government and other funding agencies, universities, professors, and enterprises) were connected by contractual and/or ownership ties and specifically the most productive scientists tended to collaborate with firm scientists or be affiliated with the private companies. Ties for knowledge development may overcome the issue on localized knowledge in the creation of a community. In other words, community creation can be facilitated by ongoing interactions of diverse social actors and help attract those who are likely to utilize (or further develop) the specialized knowledge.

It has been argued that overarching structures facilitate social relationships between diverse social actors (e.g. DiMaggio, 1982, 1991; Aldrich & Ruef, 2006). Based on this, I argue that these structures may be an antecedent of community creation. Explaining creation of high culture in Boston, DiMaggio (1982) characterized the Museum of Fine Arts and the Boston Symphony Orchestra as 'formal organizations whose official structure was draped around the ongoing life of the group that governed, patronized, and staffed them' (p. 45). He argued that the proliferation of art museums was created by the efforts of a few professional organizations (DiMaggio, 1991). These findings can be applied to emergence of new organizational forms. The creation of a community based on a new technology, there are organizational forms analogous to the professional organizations in Boston, which can organize and govern activities in diverse technological realms. Organizational forms can increase awareness of a new technology, and attract potential adopters – trade associations, for example (Aldrich & Ruef, 2006). Robinson and colleagues (2007) proposed that technological agglomeration, defined as 'the geographic co-location of different scientific and technological fields' (p. 871), can be created through overarching structures to coordinate diverse fields to develop the knowledge, called technology platforms (p. 872), defined as 'a set of instruments which enables scientific and technological production' (Robinson, et al., 2007: p. 872).

This study postulates that these overarching structures exist as *technological systems*. In prior literature, technological systems have been defined as 'knowledge and competence networks supporting the development, diffusion, and utilization of technology in established or emerging fields of economic activity' (Carlsson, 1997; p. 2). However, the definition is industry-oriented. That is, technological systems have been focus on corporate efforts for technology innovation. Accordingly, the character of specialized knowledge is not specified in the term. To incorporate the local nature of knowledge and refine Carlsson's definition, I define technological systems as 'regional sources of knowledge and competence (i.e. the presence of local scientists, university educational programs, patents filed by regional organizations) that develop and diffuse technical and scientific knowledge in emerging fields of science.' Through technological systems, scientific knowledge can be shared and the growing visibility of the knowledge can help create new firms. Specifically, technological systems enhance the visibility of new science and novel technology, promote knowledge spillovers, assist identity construction, and attract entrepreneurs to apply the new technology to new business opportunities. As a result, many industrial organizations located in separate existing populations and communities may increasingly become involved in developing and commercializing a new technology.

This study focuses on the role of technological systems in the emergence of a new community. While technological systems are structures primarily from academia and government, they also include for-profit organizations (firms, suppliers, and customers), and other organizations related to technology commercialization. By tracing the emergence and evolution of technological systems at the regional level, I will examine how new knowledge created in a scientific realm influences the emergence of industrial communities through technological systems.

Specifically, in the field of nanotechnology, I will hypothesize the relationship between growth of technological systems and emergence of a new nanotechnology-based community.

The size of technological systems has dual dimensionality: depth and breadth. Depth of technological systems is defined as the number of system components, which refer to organizations which are involved in nanotechnology development. Breadth of technological systems is defined as the number of subsystems, which refer to the activities to develop nanotechnology, such as creation, diffusion, and utilization. The emergence of a nanotechnology-based community is defined as the likelihood that new commercial organizations dedicated to nanotechnology will appear in a region and the likelihood that different populations (also known as industries) attend to nanotechnology. These variables are measured in each region by year between 1959 and 2004. With the measures, I test the hypotheses by using Cox proportional hazards models. Results of the estimation models are presented and interpretations of the findings are discussed.

THEORETICAL BACKGROUND

The Emergence of a Science-Based Community

While several scholars have defined the concept of community (Astley, 1985; Freeman & Audia, 2006; Ruef, 2000; Aldrich & Ruef, 2006), Astley (1985)'s definition is the most applicable to the study of nanotechnology community. He defined a community as 'sets of diverse, internally homogeneous populations which depend crucially on the nature of the technologies on which the populations are based' (Astley, 1985: p. 224). Freeman & Audia (2006) conceptualized a community as 'sets of relations between organizational forms or as places where organizations are located in resource space or in geography' (p.145). While Astley (1985) and Freeman & Audia (2006) focused on organizational communities as functionally integrated systems with regard to interdependencies, others have emphasized the role of social identity. Ruef (2000) defined an organizational community as 'a bounded set of forms with related identities' (p. 658) where identity refers to 'the collective identity of a class of organizations' (p. 661). Aldrich & Ruef (2006) defined an organizational community as 'a set of co-evolving organizational populations joined by ties of commensalism and symbiosis through their orientation to a common technology, normative order, or legal-regulatory regime' (p. 243).[12] While individual organizations have goals and distinctive boundaries, communities have relatively blurred boundaries because their goals and identities are not uniformly defined for all community members.

Based on the definition of a community, community emergence can be understood as a product of inter-relationships between several populations (Astley, 1985; Ruef, 2000; Aldrich & Ruef, 2006). A community can be said to emerge when distinc populations increasingly adopt the same knowledge through ongoing inter-organizational interactions. In particular, when we consider communities in which members develop, exchange, and commercialize their own scientific knowledge, we may have distinct mechanisms of their emergence. A science-based community is one where community members are involved in the development of scientific knowledge, such as biotechnology or semiconductor (e.g. Ponds & Oort, & Frenken, 2010). Specifically, Pavitt (1984) classified science-based industries as the sectors in which "main sources of technology are the R&D activities of firms…, based on the rapid development of the underlying sciences in the universities and elsewhere" (p. 362). Thus, science-based firms "invest relatively heavily in R&D and collaborate intensively with academia" (Ponds et al.,

[12] In their definition, commensalism refers to competition and cooperation between similar units and symbiosis refers to mutual interdependence between dissimilar units.

2010: p. 233). As a consequence, science-based communities consist of not only populations of science-based firms but also their research collaborators in academia and elsewhere.

The emergence of a science-based community shows three distinctive characteristics in its process. First, knowledge may be created through networks of organizations (Swan & Scarbrough, 2005; Lorenzen & Maskell, 2004; Shearmur, 2012; Arikan, 2009). Swan & Scarbrough (2005) defined networked innovation as 'innovation that occurs through relationships that are negotiated in an ongoing communicative process, and which relies on neither market nor hierarchical mechanisms of control' (p. 916). Through innovation systems based on network relationships, social actors can disseminate and adopt new scientific knowledge. Arikan (2009) emphasized that inter-firm knowledge exchanges can enhance knowledge creation.

Second, a science-based community is composed of two pre-existing communities: academic and industrial communities. In an academic community, new knowledge based on science is created and some of the knowledge may be commercialized via drawings, prototypes, a physical product, or other physical manifestation of knowledge (e.g. Håkanson, 2010). For the emergence of a new science-based community, two different communities should be integrated in the scientific knowledge. Because of that, overarching structures which help coordinate, govern, and control the distinct communities are necessary (e.g. DiMaggio, 1982, 1991; Larson & Starr, 1993; Oliver, 1990).

Third, a science-based community is geographically bound as the core scientific knowledge tends to be localized (Zucker et al., 1998). As scientific knowledge has been developed, it becomes hard to imitate or exclusively limits its adopters. In other words, in implementing the excludable knowledge, geographical distance matters (e.g. Funk, 2014), because proximal social actors can have more opportunities to obtain the new knowledge or instruments which help implement the knowledge. Consequently, science-based communities are bounded in geographical locales, even though the core scientific disciplines are shared across the communities (e.g. Saxanian, 1994).

A Systems Perspective for Community Creation

Both community ecologists and institutional theorists address the role of overarching structures which facilitate the emergence of new organizations (Astley, 1985; Aldrich & Ruef, 2006). Aldrich & Ruef (2006) argued that organizational communities set the context within which new populations emerge, because organizational communities reflect changes in societal norms and values, changes in laws and regulations, and developing technological innovations (p. 251). Institutionalists hold that repeated interactions between social actors (individuals or organizations) are typified, which constitutes social reality (Berger & Luckman, 1967; Tobert & Zucker, 1983). The social reality, based on shared understandings of practices, is seen as different kinds of organizations or collectivities of social actors. These organizations, in turn, can facilitate the process of gradual stability of social interactions (e.g. Greenwood, Suddaby, & Hinings, 2002). In particular, the process is called structuration. Van de Ven & Garud (1989) specified the structuration process, which consists of '(1) an increase in the extent of interaction among organizations in the [organizational] field, (2): the emergence of sharply defined inter-organizational structures of domination and patterns of coalition, (3) an increase in the information load with which organizations in a field must contend, and (4) the development of a mutual awareness among participants in a set of organizations that they are involved in' (p. 205).

This structuration process suggests that the relationships of social actors will be crystalized (or institutionalized) over time. Larson & Starr (1993) argued that as socioeconomic relationships converted from informal ties are developed, the networks result in crystallization. Crystallization of networks is 'characterized by a higher level of stability and predictability than was previously evident' (p. 11). This suggests that social actors will crystallize or formalize their inter-organizational relationships to make the relationships stable and predictable. Thus, the conception that relationships are crystalized and institutionalized is important because it sheds a light on how the systems are enacted by social actors.

This conception of crystalized networks can be understood in a systems perspective of organizations. In organization theory, a system is recognized as 'an assemblage or combination of parts whose relations make them interdependent' (Scott & Davis, 2006: p. 88). In addition, Katz and Kahn (1978) put, "All social systems, including organizations, consist of the patterned activities of a number of individuals. Moreover, these patterned activities are complementary or independent with respect to some common output or outcome: they are repeated, relatively enduring, and bounded in space and time." (p. 20). From this perspective, we can understand that when social relationships are crystalized, the inter-dependence constitutes a system-like structure. As the perspective suggests, interdependence between the system elements can be structured as an organization, which in turn enables the elements to reinforce their interdependence. Similarly, Van de Ven & Garud (1989) illustrated this process to explain the early stage of cochlear implant industry. They recognized that the new industry, which is created through the crystalized inter-organizational networks, consists of 'the key firms and actors that govern, integrate, and perform all of the functions required to transform a technological innovation in to a commercially viable line of products or services delivered to customers' (p. 206).

Technological Systems in the Systems Perspective

Since systems are composed of a multitude of relationships, it is useful to describe the system's configuration. In the systems perspective, the "relationship" doesn't imply only social interactions between social actors (whether organizations or individuals), but it also considers associations among cognitive or cultural aspects (Scott & Davis, 2006). For example, Van de Ven & Garud (1989) specified the structure of an industry social system as composed of three subsystems: instrumental subsystem, resource procurement subsystem, and institutional subsystem. The instrumental subsystem is drawn from the 'traditional industrial economic definition of an industry' (p. 206). In the subsystem, there are firms, suppliers, and vendors. The resource procurement subsystem, which refers to the 'basic resources necessary to support proprietary instrumental activities' (p. 207), includes any kinds of resource for the industry, such as scientific or technological knowledge, financial resources, human resources, etc. Last, the institutional subsystem indicates the 'rules and norms of the society in which organizations function' (p. 209). The subsystem includes industry governance structures, industry rules or regulations.

If we adopt the systems perspective in technological fields, technological systems will consist of social actors enacting the systems, resources on which technological innovations are based, and institutional rules reinforcing social interactions for technological development. In prior literature, technological systems are understood as 'knowledge and competence networks supporting the development, diffusion, and utilization of technology in established or emerging fields of economic activity' (Carlsson, 1997; p. 2). In terms of the interdependence between system components, the definition of technological systems varies in previous research. Podolny & Stuart (1995) reviewed the social constructionist view of technological systems: 'the dense pattern of relations concatenating the innovations and associated actors' (p. 1227). With this viewpoint, they conceptualized niche structures as 'the number and the pattern of relations that connect the innovations in a niche' (p. 1230). Barnett (1990) posits that based on a systemic technology, organizations can be networked. Systemic technology refers to 'multiple, interdependent components are linked via sophisticated interfaces to create the end-product' (Rosenkopf & Tushman 1998: p. 323). Rosenkopf & Tushman (1998) illuminated the roles of cooperative technical organizations in technology development. A cooperative technical organization is defined as 'a group that participates in technological information exchange, decision-making or standards-setting for a community' (p. 315). Those studies viewed technological systems as networks among social actors around a given technology.

On the other hand, Carlsson & Stankiwicz (1991) defined a technological system as 'a dynamic network of agents interacting in a specific economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion, and utilization of technology' (p. 93). In their definition, "agents" refer to multi-level social entities, including firms, clusters, countries, etc. With the definition, they emphasized that technological systems should be understood as 'knowledge/competence flows rather than flows of ordinary goods and services' (p.111). Following the definition of technological systems, Carlsson (1997) considered technological systems as 'knowledge and competence networks supporting the development, diffusion, and utilization of technology in established or emerging fields of economic activity' (Carlsson, 1997; p. 2). Carlsson & Jacobsson (1997) specified the technological systems of factory automation in Sweden as economic competence (e.g. users and suppliers), institutional infrastructure (e.g. education and government policy), and the clustering of resources (e.g. supporting institutions and user-supplier linkages). Consistently, Jacobsson & Philipson (1997) explicated the technological systems in Sweden with higher education, economic competence, and government technology policy. These empirical cases show that technological systems include institutional forms, such as education, government activities, other institutions supporting certain technology, etc. That is, technological systems are not a simply physical collectivity of social actors, but they include all kinds of practices and logics that social actors can enact for technology development.

Related Concepts to Technological Systems

This kind of enacted environment has been widely studied as innovation systems (e.g. Moulaert & Sekia, 2003; Miyazaki & Islam, 2007; Oinas & Malecki, 2002), clusters (Lorenzen & Maskell, 2004; Arikan, 2009), innovative milieux (Crevoisier & Maillat, 1991; Maennig & Ölschläger, 2011), industrial systems (Saxenian, 1994), and technological regimes (Nelson & Winter, 1982). Most innovation systems, which have been studied to trace technology development, are largely concerned with the conditions for innovative activity in a region (Oinas & Malecki, 2002; Moulaert & Sekia, 2003). The term, "innovation systems", has been applied to national innovation systems (NISs) bound by nations or states, regional innovation systems (RISs) bound by specific regions, and spatial innovation systems bound by overlapping and interlinked national, regional and sectorial territories (Oinas & Malecki, 2002). European scholars have identified regional innovation systems as *innovative miliux*. This concept was introduced through GREMI (Group de Recherche Européen sur les Milieux Innovateurs) (see

Camagni, 1991a). Camagni (1991a) defined an innovative milieu as 'the set, or the complex network of mainly informal social relationships on a limited geographical area, often determining a specific external image and a specific internal 'representation' and sense of belonging, which enhance the local innovative capability through synergetic and collective learning processes' (p. 3). An innovative milieu, through the informal social relationships, helps facilitate knowledge exchange (including tacit knowledge), foster mutual trust, and create social capital within a region (Camagni, 1991b). As a result, within the milieu, the decisions of diverse social actors are coordinated and interactive learning is accelerated (Camagni, 1991a; 1991b). As an empirical study, Maennig & Ölschläger (2011) identified innovative milieux as associations and chambers of commerce and industry and found that the density and expenditures of the organizational forms in Germany influenced the region's innovation, represented by the business start-up rate and patent intensity.

"Clusters" are another term applied to enable the tracing of technology development. According to Arikan (2009), clusters, conceptualized as 'venues of enhanced knowledge creation' (p. 658), facilitate knowledge exchanges among cluster firms, enable inter-firm knowledge exchanges to be materialized, and provide a place where firms that lack valuable knowledge conglomerate. In clusters, technology is exchanged, and the potential for knowledge exchange can attract new cluster member firms. Similarly, Saxenian (1994) observed that Silicon Valley showed the complex of institutional and social relationships that connect the producers within the region's fragmented industrial structure. She perceived this social structure as an industrial system, which illustrates "the historically evolved relationship between the internal organization of firms and their connections to one another and to the social structures and institutions of their particular localities" (p. 7).

Beyond geographical boundaries, epistemic boundaries have been also considered. For example, “technological regimes” are used to identify non-regional technological systems. Nelson & Winter (1982), attempting to explain continuing technological progress over time, proposed a structure which functions to guide the evolution of certain technologies, called “technological regimes”. They applied Hayami & Ruttan (1971)’s concept of ‘meta production function’, which refers to ‘a frontier of achievable capabilities, defined in the relevant economic dimensions, limited by physical, biological, and other constraints, given a broadly defined way of doing things’ (Nelson & Winter, 1982: p. 258). Technological regimes also include cognitive elements, for example social actors’ beliefs about the feasibility or legitimacy of a technology. Accordingly, the boundary of a technological regime is not spatially bounded, but rather determined depending on social actors’ beliefs on a technology.

Structure of Technological Systems: Subsystems and Components

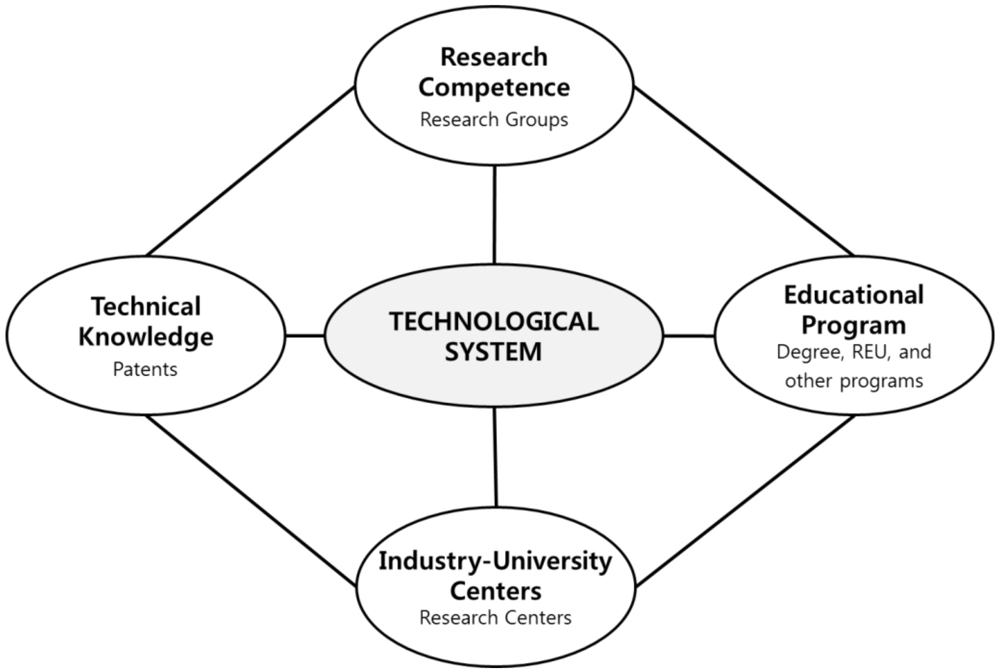
As discussed, the systems perspective recommends that technological systems should be treated as one entity rather than the collectivities of isolated entities, because of the interdependence among the entities in the systems. This holistic approach gives a different lens to investigate technological systems: technological systems are understood as structured wholes rather than collectivities of isolated components. As such, we need to consider the structural features of technological systems significantly rather than their attributional features. To identify the structural features of technological systems, I discern subsystems and their components.

The subsystems of technological systems include cognitive or cultural aspects (Scott & Davis, 2006; Van de Van & Garud, 1989), which are reflected by various activities in the development of new knowledge (or technology). According to the definition of technological systems, three activities are identified in technological systems: development, diffusion and utilization. The activities regarding technology development is related to how social actors create new technology or its applications. For example, research groups under control of one faculty member or multiple faculty members are formed to create or develop new knowledge or technology. The activities on diffusion are exemplified as education/training programs or university-industry research consortia. Any coalition activities between academics and industries can facilitate knowledge diffusion. Lastly, the utilization of technology is related to the outcome of research. Patents or other institutional supports for technology transfer are the artifacts for utilization of technology.

These activities are embodied by diverse social actors (individuals, groups, and organizations), which constitute a subsystem. In other words, each subsystem represents the coordinated activities for the development, diffusion, or utilization of a technology, and within the subsystem, social actors interact with one another. Social actors within each subsystem are called components. Even though social actors of each subsystem are differentiated in terms of their activities, they play a common role as an adopter of the new knowledge or technology. In the conception of subsystems and components, technological systems are characterized with a multi-layered structure: multiple subsystems are integrated through certain technology, and their meanings or activities are implemented by their components.

Figure 3-1 depicts the structure of technological systems, consisting of the components and subsystems of technological systems.

FIGURE 3-1: SUBSYSTEMS AND COMPONENTS OF TECHNOLOGICAL SYSTEMS



HYPOTHESES

Size of Technological Systems and Emergence of de Novo Foundings

From the systems perspective, I argue that size of a technological system can influence emergence of new organizations. Given that technological systems are identified with subsystems and components, the size of technological systems depends on the respective size of subsystems and components. First, the size of subsystems at a region represents how various activities are inter-related to constitute a technological system. As a region includes different kinds of subsystems, the activities to develop new technology can be diversified. These diversified activities for knowledge development are called breadth of technological systems.

That is, the greater breadth of technological systems in a given region, the further the knowledge can be developed and utilized. Specifically, as the number of subsystems increases within a technological system, the feasibility of the technology can be reinforced with the increase in the variety of subsystems (i.e. breadth). For example, research activities can be further developed in industry-university consortia or other professional organizations (e.g. Hunter, Perry, & Currall, 2011). This suggests that the feasibility of new scientific knowledge makes actors, including nascent entrepreneurs, commonly believe in the technology and take its utilization for granted (Green, 2004). Technological systems, especially the presence of various subsystems, facilitate the process where such beliefs are collectively mobilized (Bonaccorsi, 2008). In other words, the greater breadth of technological systems in the emerging field enables social actors (especially entrepreneurs) to consensually believe the feasibility of scientific knowledge. Thus, the breadth of technological systems can have a positive impact on de novo firm formation, which composes the first hypothesis in this study.

H_1. The greater is the breadth of technological systems, the greater the number of de novo foundings.

In addition, within-subsystem activities can be considered another dimension for the size of technological systems. As many social actors are involved in the development of new knowledge in a region, the region can demonstrate its reputation or prestige on the knowledge. As discussed, since components of a subsystem are the products of the interactions among social actors for the purpose of the subsystem, the size of components in a region can indicate the extent to which the activities for knowledge development by social actors are intensified in that region. This is called depth of technological systems. I argue that the depth of technological systems also will have a positive effect on new firm foundings. As the number of the social actors who share the common technology extensively increases, more social actors are willing to involve in the development of the technology. Powell et al. (2005) found that the emergence of a field is likely to unfold when diverse social actors are located in a common technological community, which helps foster the social interactions regarding the technology development. This means that technological systems, especially the presence of intensified components, helps gain the legitimacy of the technology from diverse populations. In particular, as technological systems can further attract more people who intend to commercially utilize the technology (i.e. entrepreneurs), the attraction of entrepreneurs can trigger the creation of organizations. Therefore, I hypothesize that the depth of technological systems can help facilitate the emergence of de novo firm foundings.

H_2. The greater is the depth of technological systems, the greater is the number of de novo foundings.

Size of Technological Systems and Population Differentiation

As technological systems grow in terms of depth and breadth, the populations who commercially utilize the technology become diversified. In other words, the science-based community includes different commercial populations (i.e. industries) with the size of technological systems. I call this process population differentiation. There are three mechanisms where populations within the science-based community are differentiated. Specifically, as scientific knowledge is created and developed in certain populations, external organizations begin using the evidence of the habitualized knowledge[13] in the populations by collaborating with those who are located in the populations where scientific knowledge is developed. Inter-population collaboration for the development of scientific knowledge will thus increase the number of populations who accept the feasibility of the scientific knowledge. Second, as the membership of professional associations supporting scientific knowledge, like research centers in academic communities, or educational organizations that provide formalized educational programs etc., increases, the subfields of scientific knowledge are extensively differentiated and the science-based community has diverse sub-populations. As a result, each sub-population has its own collective identity. Last, scientific knowledge itself can be differentiated (e.g. Maennig & Ölschläger, 2011). The proliferated technological systems specify the sub-fields dedicated to a scientific knowledge. New knowledge is drawn from the combination with existing scientific knowledge in each sub-population and as a result, the science-based community includes the sub-populations dedicated to the specified scientific knowledge. Therefore, a set of hypotheses regarding population differentiation is proposed:

H_3. The greater is the depth of technological systems, the greater the population differentiation.

H_4. The greater is the breadth of technological systems, the greater the population differentiation.

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[13] Tolbert & Zucker (1996) defined habitualization as 'the development of patterned problem-solving behaviors and the association of such behaviors with particular stimuli' (p. 181). Based on this definition, habitualized nanotechnology refers to nanotechnology whose utilization to achieve a goal is patterned in a population.

METHODS

Research Settings

To test these hypotheses, the empirical setting investigated is the field of nano-science and technology. Nano-science and technology is a good setting to illustrate the role of scientific collaboration in the emergence of technological systems because we can clearly identify multiple organizations from diverse populations based on the same underlying technology. In fact, the nano- science and technology field includes organizations in both academia and industry, such as universities, research institutes, and new companies, participating in development of nano-scale materials and products (Bonaccorsi & Vargas, 2010; Meyer & Persson, 1998; Selin, 2007). As such, we can specify the structure of technological systems rigorously.

The empirical tests of the hypotheses start with the geographic consideration of the technological systems. That is, the unit of analysis is a geographic region in the U.S., and indicated several ways: by county, by state, by a functional economic area or an MSA (metropolitan statistical area), for example. Building on Zucker et al. (2007) who considered "functional economic areas (i.e., central urban areas plus their suburbs and exurbs as "regions")" (p. 856), defined by the U.S. Bureau of Economic Analysis, as the units of analysis, I examined 182 functional economic areas to investigate how U.S. regions have commercialized nanotechnology through technological systems over time. The time span of this study is between 1959 and 2004. The first date, 1959, is selected because Richard Feynman first articulated the idea of nanotechnology theoretically. The data collection stops in 2004, which the right truncation year.

Estimation Models

This study claims that the emergence of new for-profit organizational forms dedicated to nanotechnology (i.e. de novo firms and the emergence of differentiated populations) is influenced by the size of technological systems. To test the hypotheses, the emergence of de novo firms and differentiated populations dedicated to nanotechnology is estimated from depth and breadth of technological systems. This study operationally assumes that the emergence of de novo firms and differentiated populations is commonly followed by a Poisson process with the equation below:

$$\lambda_t = \lim_{\Delta t \to 0} \frac{P(t < T < t + \Delta t \mid T \geq t)}{\Delta t} \tag{1}$$

Based on this, I adopt a Cox proportional hazard model to estimate the hazard rate of de novo foundings and the hazard rate of population differentiation. To control the possible reverse causality, I use one-year lagged values of the predictors and the control variables.

Measures

Dependent variables. The dependent variables are de novo foundings and population differentiation. De novo firms are defined as 'a private firm founded independently for the purpose of developing, manufacturing, and selling components on the merchant market (called merchant producers)' (adopted from Beckman et al., 2014: p. p. 466). Based on this definition, de novo foundings is measured as the number of nanotechnology-based de novo firms founded at a given region between 1959 and 2004 (Schoonhoven, 2009). To identify dedicated nanotechnology de novo firms, five criteria are applied: (1) they did not previously exist; (2) their first product or technology is derived from nano-science; (3) they do not produce any other product or technology in any domain other than nanotechnology at founding; (4) they are private, independent start-ups; and (5) they are not organizations whose starting events were the result of mergers or former corporate divisions or business spun-off from an existing organization (Schoonhoven & Kim, 2010). In total, 222 de novo firms are identified between 1959 and 2004. Regarding de novo firms, I coded 1 for each region when one or more de novo firm were founded in a given year in the region; 0 otherwise.

For population differentiation, defined as the extent to which subpopulations for nanotechnology are differentiated from existing populations at a given region, I measure the appearance of new populations in the region. When we identify the new firm emergence at a given region, we can also discern each firm's population identity, which can be technically identified by SIC (Standard Industrial Classification) codes. Even though new firms are dedicated to nanotechnology, the industrial classification for nanotechnology firms is not formalized, but rather they are classified within existing industries related to nanotechnology. Thus, through the SIC codes to which the new firm is assigned, we can measure how many different populations join the nanotechnology-based community. In other words, the populations discerned by firm foundings can indicate events where different populations enter the nanotechnology community and the number of populations within the community refers to the degree of population differentiation. Assuming that population differentiation is initiated when two or more new populations enter the community, as defined, I coded 1 when a region has the first two or more populations. Populations are identified with 2-digit SIC codes of de novo firms dedicated to nanotechnology.

Independent variables. As for size of technological systems, there are two measures: depth and breadth. Depth refers to the number of social actors involved in development of nanotechnology and breadth denotes the number of activities related to nanotechnology development, the growth of technological systems is specified into how many components and subsystems are located in a given region. Breadth is defined as the extent to which new types of subsystems emerge in a region and depth is defined as the extent to which new components of any subsystems emerge. Those are measured as the count numbers of subsystems and components traced between 1959 and 2004 respectively at the given region.

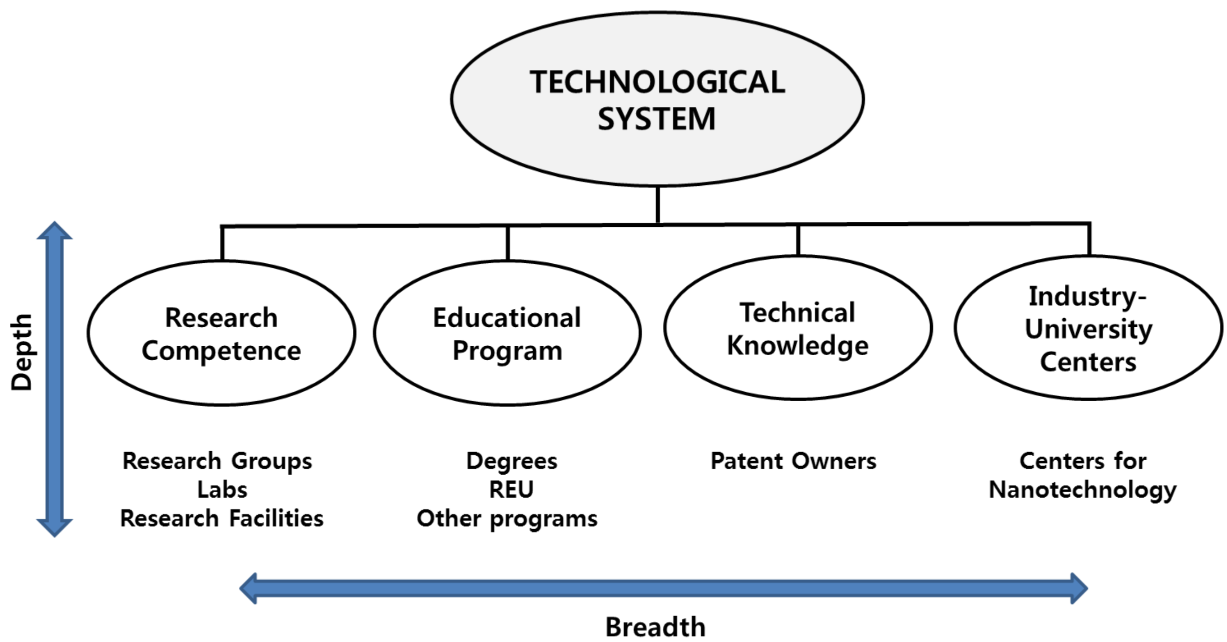
In this study, technological systems have four dimensions: (1) research competence, (2) education programs, (3) industry-university centers, and (4) technical knowledge. Research competence refers to technology development, which provides technological opportunities. All the entities and practices regarding scientific research, such as research groups, research labs or any types of collaborations within or between universities, are components of research competence. Research competence is measured as the number of research groups of scientists who develop nano-science and technology. There are two kinds of research groups: explicit research groups and implicit research groups. While the explicit research groups have the term of "nanotechnology" in their group names or their mission statements explicitly, the implicit research groups are those who came from other scientific disciplines, such as materials science, and then began research in nanotechnology. Implicit research groups are counted as an element of research competence when the first scientific article based on nano-science and technology is published. Research groups are listed in the directories of *Nanotechnology Now* (http://www.nanotechnology-now.com) and the number of research groups in each region is annually traced between 1959 and 2004.

Educational programs in universities provide ways to reproduce scientific knowledge. Through educational programs, such as degrees or departments in universities, including REU (Research Experience for Undergraduates), potential scientists who can develop the knowledge can be trained. Education programs are those awarding academic degrees in nanotechnology or university-based Research Experience for Undergraduates programs (REUs) for nanotechnology. While the definition of educational programs is straightforward, it is not possible to accurately identify when a department was formed. In this study, the number of departments is counted only when a university explicitly provides degree programs or courses in nanotechnology. The establishment of REUs is traced over time to capture educational programs. Given that universities inherently function to disseminate knowledge and educate students, other specialized educational programs can indicate the commitment of a university to activities for knowledge dissemination. The number of REUs in a region by year measures the education programs. The departments and REUs between 1959 and 2004 are derived from the directories of *Nanotechnology Now* (http://www.nanotechnology-now.com).

Industry-university centers, such as research centers, conferences, trade associations, or innovative milieu, enable social actors from both industries and universities to exchange knowledge and resources. As a location for interaction between universities and industries, Industry-University Centers provide opportunities where diverse industrial populations, including academics, further develop scientific knowledge. Accordingly, Industry-University Centers are defined as university-based organizational forms which function to facilitate interactions between academia and industries. The component is typically represented by research centers embedded in universities. However, the name of "research center" is widely used in universities. For example, research groups formed by faculty members also can be named as a "research center". To differentiate from the components of research competence named "research centers", I consider only the research centers which have a function to bridge academia and industries as industry-university centers. Also, this subsystem includes government funded research centers, such as Materials Research Science and Engineering Centers (MRSECs), National Nanotechnology Infrastructure network (NNIN), Centers of cancer nanotechnology (CCNEs), or any kinds of research centers which National Science Foundation (NSF) support to create and develop nanotechnology, and the research centers funded by private foundations, national labs, or state government, both of which are resided in a university. Thus, industry-university centers are listed from the directories of *Nanotechnology Now* (http://www.nanotechnology-now.com) and measured as the number of the university-based research centers featured with industrial interactions, located in each region of the U.S. annually between 1959 and 2004.

Last, technical knowledge consists of organizations by which scientific knowledge is commercially codified, specifically through patent activities. Patenting activities facilitate transforming scientific knowledge to actionable knowledge which can be more easily commercialized. As a result, technical knowledge can provide business opportunities as well as scientific opportunities. In this study, technical knowledge is measured as the organizations owning patents which are classified into nanotechnology. To identify the nanotechnology patents, I used the patents filed with the United States Patent and Trademark Office (USTPO). With the patent data, Zucker, Darby, & Fong (2011) identified nanotechnology-relevant patents, based on a "keyword" search. Following their classification methods, the number of the nanotechnology-relevant patents filed is counted from 1959 to 2004 by region. For the geographical origins of the patents, I used the first inventors' address. Then, the number of organizations in which the patent authors are affiliated is counted by region and year, which constructs a measure of technical knowledge. To differentiate this from research competence, universities are excluded from the technical knowledge subsystem. Figure 3-2 depicts the breadth and depth of technological systems.

FIGURE 3-2: BREADTH AND DEPTH OF TECHNOLOGICAL SYSTEMS



Control variables. Control variables are specified in terms of resource mobilization for entrepreneurship, density dependence, and socio-economic characteristics of the region. First, financial resources are considered a control because it indiates resource mobilization. Financial resources available for new nanotechnology-based firms may derive from Venture Capital funds. This indicates a macro-economic condition and environmental munificence for high-technology venture firms respectively (c.f. Castrogiovanni, 1991). The greater the available funds, the greater the likelihood of organizational foundings. VC funds are measured as the annual amount of VC funds available, which is collected from Thomson One Database (formerly VentureXpert database).

Adopting the density dependence theory of population ecology (Hannan & Freeman, 1987), the size of firms established in the prior time spell is also considered as a control variable. This study mainly focuses on the early stage of the development of nano-science, so instances of firm failures are empirically rare events. Thus, instead of measuring density as the cumulative number of technological systems, prior foundings (as the rate of change in density) is more helpful to predict the emergence of technological systems. I expect the inverted U-shaped relationships between the prior foundings and the emergence of technological systems. However, at the early stage of community creation, the negative effect of prior foundings indicating competition among existing firms tends to be insignificant (Schoonhoven & Kim, 2010). Accordingly, I consider a positive linear effect of prior foundings.

The density of neighbor regions is also considered as a control variable to control the effect of spatial contagion (Greve, 2002; Cattani, Pennings, & Wezel, 2003; Burt, 2010). Spatial-contagion theory deals with "how geographically delineated subpopulations grow and interact with neighboring subpopulations" (Greve, 2002: p. 847). That is, in addition to the co-located social actors, the social actors located in neighboring regions also can influence the formation of technological systems as they can provide some resources for the development of nano-science or nanotechnology. Nearby regions are defined as the geographically adjacent regions of the focal region. To identify the nearby regions, I create an adjacency matrix or regions which show which regions share borders (e.g. Greve, 2002). With the adjacency matrix, the number of technological systems at a given region is counted and summed by year between 1959 and 2004.

Last, various socio-economic characteristics in the region are considered as control variables: average wage per job and total population. The average wage per job serves as an indicator of income growth (Darby & Zucker, 2005; Zucker, et al., 1998; Sorensen, 2004). The information on average wages for each region is collected from Bureau of Economic Analysis.[14] Total population (the number of residents in a region) has been also considered an exogenous factor to influence firm formation (Barnett & Sorenson, 2002) as it can indicate potential markets (e.g. Kalnins & Chung, 2004) and the carrying capacity of a region – "the maximum number of firms that can be supported" (Dobbin & Dowd, 1997: p. 511). Total population size in each region is recorded from US Census sources[15]. In addition, year dummies are included in the models to control for autocorrelation effects.

Table 3-1 summarizes the measures of the variables described above, and Table 3-2 presents descriptive statistics of dependent variables (i.e. de novo foundings and population differentiation), independent variables (breadth and depth), and control variables (prior foundings/populations, VC funds, personal income growth, and population growth). Furthermore, to empirically illustrate the overview of technological systems, the statistics of the components of each subsystem are also included in Table 3-2.

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[14] http://www.bea.gov/iTable/iTable.cfm?reqid=70&step=1&isuri=1&acrdn=4#reqid=70&step=1&isuri=1

[15] http://www.census.gov/main/www/access.html

TABLE 3-1: CONCEPTS, DEFINITIONS, MEASURES, & DATA SOURCES

Construct	Definition	Measure	Data Source
DEPENDENT VARIABLES: Emergence of Community			
de novo foundings	The likelihood that de novo firms are founded in a given U.S. region	Code 1 if two or more nanotechnology-specialized de novo firms appear at a region at time *t;* 0 else	Schoonhoven (2009)
Population Differentiation	The likelihood that industries engaged in nanotechnology are diversified in a given U.S. region	Code 1 if two or more industries (two-digit SIC codes) in which nanotechnology-dedicated firms are embedded appear at a region at time *t;* 0 else	Schoonhoven (2009)
INDEPENDENT VARIABLES: Growth of Technological Systems			
Breadth of Technological Systems	The extent to which new types of subsystems emerge in a region	The number of subsystems (i.e. research competence, educational programs, industry-university centers, and technical knowledge) in each region of the U.S. annually between 1959 and 2004	Directories of Nanotechnology-Now (www.nanotechnology-now.com)
Depth of Technological Systems	The extent to which new elements of the subsystems emerge in a region	The number of components of each subsystem (i.e. research groups, educational programs, research centers, and patent owners) in each region of the U.S. annually between 1959 and 2004	Directories of Nanotechnology-Now (www.nanotechnology-now.com)
• Research Competence	The likelihood that organizations other than universities support nanotechnology development in a given U.S. region.	The number of research groups, laboratories, and facilities at a region in the U.S. at time *t*	Directories of Nanotechnology-Now (www.nanotechnology-now.com)
• Educational Programs	The likelihood that nanotechnology education is initiated in a given U.S. region	The number of nanotechnology-specialized educational programs at a region in the U.S. at time *t*	Directories of Nanotechnology-Now (www.nanotechnology-now.com)
• Industry-University Centers	The likelihood that university-industry relations for nanotechnology development are formalized in the U.S. region	The number of nanotechnology-specialized organizational forms functioning fostering industrial relations (e.g. research centers, or forums, etc.) at a region in the U.S. at time *t*	Directories of Nanotechnology-Now (www.nanotechnology-now.com)
• Technical Knowledge	The likelihood that the knowledge on nanotechnology is officially codified in the U.S. region.	The number of organizations which apply for one or more patents dedicated to nanotechnology at a region in the U.S. at time *t*	Nanobank (www.nanobank.org) USPTO

CONTROL VARIABLES			
Prior de novo Foundings at a focal region	The rate of change in the cumulative number of de novo firms at a focal region	The number of de novo firms dedicated to nanotechnology at a foca region founded at time *t-1*	Schoonhoven (2009)
Prior Foundings at neighbor regions	The rate of change in the cumulative number of firms at neighbor regions	The total number of (1) incumbents who firstly applied their patent dedicated to nanotechnology and (2) de novo firms at the neighbo regions founded at time *t-1* * neighbor regions: the areas which share boundaries of the focal region	Nanobank (www.nanobank.org)
Prior Population Differentiation at a focal region	The rate of change in the cumulative number of industries engaged in nanotechnology at a focal region	The total number of industries (2-digit SIC) appearing with de novo firms dedicated to nanotechnology at a focal region at t-1	Schoonhoven (2009)
Prior Population Differentiation at neighbor regions	The rate of change in the cumulative number of industries engaged in nanotechnology at neighbor regions	The total number of industries (2-digit SIC) appearing with de novo firms dedicated to nanotechnology at a focal region at t-1 * neighbor regions: the areas which share boundaries of the focal region	Schoonhoven (2009)
VC Funds	The prior investment from venture capitalists for de novo foundings	The total dollar amount of venture capital funds for de novo firms at a focal region at time t-1	VentureXpert (now Thomson One)
Population Growth	The growth rate of residents at a focal region	$u_{it} = \frac{P_{it} - P_{it-1}}{P_{it-1}}$ u_{it}: The growth rate of population at region *i* at time *t* P_{it}: The total number of residents at region *i* at time *t*	US Census, 1959-2004
Personal Income Growth	The rate of change in residents' income at a focal region	$c_{it} = \frac{R_{it} - R_{it-1}}{R_{it-1}}$ c_{it}: The growth rate of personal income at region *i* at time *t* R_{it}: The gross amount of personal income at region *i* at time *t*	Bureau of Economic Analysis, 1959-2004

TABLE 3-2: DESCRIPTIVE STATISTICS

N=8372	Mean	SD	Min	Max	1	2	3	4	5	6	7	8	9	10				
1. De novo Foundings	0.04	0.31	0	9														
2. Population Differentiation	0.03	0.23	0	5	0.92													
3. Breadth of Technological Systems	0.03	0.18	0	1	0.19	0.18												
4. Depth of Technological Systems	4.22	20.21	0	457	0.63	0.56	0.24											
5. Research Competence	0.04	0.29	0	9	0.40	0.36	0.52	0.44										
6. Educational Programs	0.01	0.14	0	4	0.27	0.24	0.45	0.27	0.65									
7. Industry-University Centers	0.03	0.29	0	14	0.36	0.28	0.43	0.25	0.70	0.62								
8. Technical Knowledge	0.08	0.58	0	15	0.57	0.49	0.25	0.84	0.35	0.23	0.20							
9. Prior de novo foundings (focal)	0.03	0.29	0	9	0.62	0.48	0.18	0.58	0.40	0.28	0.35	0.56						
10. Prior foundings (neighbors)	2.36	7.13	0	119	0.20	0.19	0.22	0.26	0.24	0.18	0.16	0.25	0.19					
11. Prior pop. differentiation (focal)	0.03	0.22	0	5	0.52	0.42	0.18	0.54	0.36	0.24	0.28	0.52	0.92	0.19				
12. Prior pop. differentiation (neighbor)	0.15	0.59	0	9	0.17	0.18	0.18	0.17	0.20	0.16	0.16	0.16	0.18	0.66	0.19			
13. VC Funds (in Millions)	0.19	4.01	0	229.09	0.51	0.31	0.11	0.39	0.24	0.19	0.29	0.38	0.58	0.11	0.39	0.07		
14. Personal Income Growth	0.06	0.05	-0.10	0.51	0.00	0.00	0.00	0.02	-0.02	-0.02	-0.01	0.00	-0.01	-0.01	-0.01	-0.02	-0.02	
15. Population Growth	0.01	0.01	-0.08	0.13	0.03	0.04	0.04	0.04	0.02	0.01	0.01	0.04	0.02	0.05	0.03	0.04	0.00	0.53

RESULTS

Hypothesis Tests

Table 3-3 presents the estimations of the hazard ratios of de novo foundings with respect to the growth of technological systems. Model 1 represent the base model; Models 2 through 6 examine how each subsystem influences the founding rate of de novo firms; and Models 7 through 9 present the estimates of de novo foundings hazard ratios with respect to breadth and depth of technological systems. Of the models, Model 9 is the full model testing the hypotheses.

In Model 9, we find that both breadth and depth are positively related to the emergence rate of de novo foundings ($\beta = .022$; $p < .001$; $\beta = .868$; $p < .05$, respectively). The estimated hazard ratios of de novo foundings with respect to breadth and depth are 2.382 ($=e^{.868}$) and 1.022 ($=e^{.022}$) respectively. The estimated hazard ratios denote the multipliers which raise the emergence rate when one unit of each predictor increases. That is, when the depth of technological systems increases by one unit, the founding rate of de novo firms is 1.022 times greater than the base rate. Likewise, the emergence rate of de novo foundings is 2.382 times greater than the base rate when the depth of technological systems increases by one unit. These results support Hypotheses 1 and 2. Given that the emergence rate of de novo foundings denotes the speed at which de novo firms are founded, these results reveal that the growth of technological systems (i.e. breadth and depth) enable entrepreneurs to consider founding a firm dedicated to nanotechnology more quickly.

TABLE 3-3: COX PROPORTIONAL HAZARD MODELS PREDICTING DE NOVO FOUNDINGS FROM DEPTH AND BREADTH OF TECHNOLOGICAL SYSTEMS

	Model 1	**Model 2**	**Model 3**	**Model 4**	**Model 5**	**Model 6**	**Model 7**	**Model 8**	**Model 9**
CONTROLS									
Prior Foundings (focal)	2.078***	1.847***	1.758***	2.042***	2.127***	2.078***	1.931***	2.071***	1.985***
	(.476)	(.511)	(.523)	(.476)	(.482)	(.471)	(.479)	(.476)	(.471)
Prior Foundings (neighbor)	.029	.018	.029	.017	-.004	-.010	.022	.002	-.004
	(.023)	(.021)	(.021)	(.023)	(.022)	(.023)	(.022)	(.023)	(.022)
Prior Foundings (neighbor)^2	-.000	-.000	-.000	-.000	.000	.000	-.000	.000	.000
	(.000)	(.000)	(.000)	(.000)	(.000)	(.000)	(.000)	(.000)	(.000)
VC Funds	.180†	.216**	.203*	.198*	.212**	.223**	.204*	.175†	.194*
	(.096)	(.076)	(.084)	(.089)	(.072)	(.068)	(.087)	(.104)	(.097)
Personal Income Growth	.033	.054	.043	.031	.025	.028	.039	.000	.007
	(.056)	(.062)	(.061)	(.059)	(.059)	(.064)	(.059)	(.058)	(.060)
Population Growth	.178	.168	.178	.214†	.230†	.265*	.193	.280*	.294*
	(.127)	(.132)	(.129)	(.130)	(.125)	(.134)	(.127)	(.134)	(.135)
HYPOTHESIZED EFFECTS									
Research Competence		1.198***				.515			
		(.140)				(.324)			
Educational Programs			1.548***			.021			
			(.320)			(.639)			
Industry-University Centers				.901***		.485†			
				(.167)		(.268)			
Technical Knowledge					1.320***	1.116***			
					(.171)	(.174)			
Breadth of Technological Systems							1.020**		.868*
							(.342)		(.367)
Depth of Technological Systems								.023***	.022***
								(.004)	(.004)
2×Log Likelihood	-549.73	-521.98	-536.10	-533.22	-504.57	-489.10	-543.32	-509.67	-505.06
AIC	561.73	535.98	550.10	547.22	518.57	509.10	557.32	523.67	521.06
ΔDeviance (χ^2)	-	27.75*	13.63***	16.51***	45.16***	60.63***	6.41*	40.07***	44.67***
N (obs)	8,109	8,109	8,109	8,109	8,109	8,109	8,109	8,109	8,109
# BEAs	182	182	182	182	182	182	182	182	182

† p <.1, * p <.05, ** p <.01, *** p <.001

Table 3-4 presents estimations of the hazard ratios of population differentiation with respect to the growth of technological systems (specifically breadth and depth). The structure of Table 3-4 is identical to Table 3-3. Through Models 7 through 9, the hazard ratio of population differentiation is estimated from breadth and depth. Models 2 through 5 specify the impact of each subsystem on population differentiation.

TABLE 3-4: COX PROPORTIONAL HAZARD MODELS PREDICTING POPULATION DIFFERENTIATION FROM DEPTH AND BREADTH OF TECHNOLOGICAL SYSTEMS

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8	Model 9
CONTROLS									
Prior population differentiation (focal)	2.164***	1.894***	1.821***	2.100***	2.140***	2.065***	1.972***	2.115***	1.990***
	(.443)	(.501)	(.512)	(.453)	(.447)	(.453)	(.457)	(.458)	(.463)
Prior population differentiation (neighbor)	.368†	.185	.320	.220	.227	.126	.307	.367†	.319
	(.205)	(.202)	(.202)	(.213)	(.226)	(.228)	(.206)	(.221)	(.218)
Prior population differentiation (neighbor)^2	-.031	-.001	-.020	-.008	-.020	-.002	-.022	-.035	-.028
	(.036)	(.032)	(.033)	(.033)	(.039)	(.038)	(.036)	(.040)	(.039)
VC Funds	.235***	.250***	.251***	.237***	.233***	.237***	.248***	.214**	.224**
	(.066)	(.056)	(.058)	(.065)	(.062)	(.060)	(.062)	(.082)	(.079)
Personal Income Growth	.030	.059	.043	.035	.032	.038	.040	.000	.011
	(.059)	(.064)	(.064)	(.061)	(.061)	(.065)	(.061)	(.062)	(.064)
Population Growth	.148	.134	.148	.181	.189	.222	.167	.229†	.244†
	(.131)	(.134)	(.133)	(.134)	(.128)	(.136)	(.130)	(.138)	(.154)
HYPOTHESIZED EFFECTS									
Research Competence		1.198***				.518			
		(.154)				(.330)			
Educational Programs			1.536***			.110			
			(.325)			(.630)			
Industry-University Centers				.877***		.413			
				(.171)		(.257)			
Technical Knowledge					1.294***	1.093***			
					(.172)	(.173)			
Breadth of Technological Systems							1.039**		.838*
							(.336)		(.354)
Depth of Technological Systems								.023***	.022***
								(.004)	(.004)
2×Log Likelihood	-546.85	-519.66	-533.62	-531.21	-502.02	-487.11	-540.29	-505.63	-501.36
AIC	558.85	533.66	547.62	545.21	516.02	507.11	554.29	519.63	517.36
ΔDeviance (χ^2)	-	27.19***	13.23***	15.64***	44.83***	59.74***	6.56*	41.22***	45.49***
N (obs)	8,113	8,113	8,113	8,113	8,113	8,113	8,113	8,113	8,113
# BEAs	182	182	182	182	182	182	182	182	182

† p <.1, * p <.05, ** p <.01, *** p <.001

For the estimation of the emergence of population differentiation, we find consistent results. That is, as seen in Model 9, the emergence of population differentiation is positively related to both breadth and depth (β = .838; p < .05; β = .022; p < .001, respectively) and the estimated hazard ratios are 2.311 (=$e^{.838}$) and 1.022 (=$e^{.022}$) respectively. Those results, supporting Hypotheses 3 and 4, reveal that the depth and breadth of technological systems increase the speed of population differentiation within a nanotechnology-based community. That is, as technological systems grow, the tendency of population differentiation is more likely to occur.

Therefore, it is concluded that the size of technological systems, represented by their sub-dimensions, breadth and depth, helps speed the entry of new commercial organizational forms (including firms and industries), increasing the likelihood of a nanotechnology-based community emerging.

Specification of Subsystem Effects on the Emergence of a Community

In Table 3-3, Models 2 through 5 reveal that the growth of each subsystem (i.e. research competence, educational programs, industry-university centers, and technical knowledge) positively influences the de novo founding rates. However, when the subsystems are considered in the additive model (Model 6), the effects of most subsystems become insignificant. Likewise, the comparison between Model 6 and Model 9 in Table 3-4 shows results consistent with those in Table 3-3. Each subsystem is positively related to the population differentiation rate when it is included in the estimation model one by one. Yet, when the subsystems are simultaneously considered in a model (shown in Model 6), all but technical knowledge (such as research competence, educational programs, and industry-university centers) fade to non-significance.

From the somewhat inconsistent results, the fairly high correlations among the subsystems (shown in Table 3-2) suggest estimation biases. Actually, these biases can be statistically ignored as the VIFs (Variance Inflation Factors) of Model 6 are not as large as 10, which is the threshold to determine multicollinearity (Greene, 2002). However, the interpretation of these results may be misleading by de-emphasizing the role of the subsystems which turn out insignificant in Model 6 (such as research competence and educational programs). Even though specifying subsystems as an independent entity is valuable implications, the character of interdependence in technological systems may prevent it from making valid interpretations from the additive model. In this sense, as a holistic approach, the conception of breadth and depth of technological systems can help understanding the role of technological systems in emergence of a new community.

DISCUSSION AND CONCLUSION

This study argues that the growth of technological systems (in terms of breadth and depth) will increase the establishment of de novo firms dedicated to nanotechnology, and also it will also facilitate population differentiation, resulting in creation of a new community based on nanotechnology. From these findings, we can understand the role of technological systems in the process of community creation. Specifically, I claim that technological systems help incorporate the concept of localized knowledge into an explanation of community creation. A new community can be created when diverse, multiple organizations are involved in developing common knowledge, and knowledge sharing among social actors is facilitated by technological systems. In particular, by connecting diverse social actors, technological systems foster inter-relationships between heterogeneous organizations, an essential characteristic of a community. As such, the creation of a social structure around new knowledge is a precursor of community creation. This suggests that technological systems provide not only an alternative mechanism for community creation, but also an opportunity to integrate fragmented theories from different disciplines to capture the conjecture that collaboration can lead to the transmission of localized knowledge and also attract diverse organizations, including new organizational forms.

First, the significant relations between size of technological systems (depth and breadth) and the emergence of a nanotechnology-based community suggest that the repeated interactions between social actors (individuals or organizations) are typified into a multi-layered social structure composed of diverse organizational forms. The community, based on shared understandings of new knowledge, is seen as different kinds of organizations or collectivities of social actors. In this sense, technological systems provide a platform for knowledge transmission by opening the possibility to exchange scientific knowledge with these organizations. In particular, since diverse social actors can actively share new knowledge through technological systems, technological systems help overcome knowledge localization constraints and thus lead to the creation of a new science-based community by embracing diverse social actors.

Second, the presence of technological systems can be understood as a resource structure. As technological systems grow, the resource structure for entrepreneurship opens, allowing more potential adopters. The resource structure reflected by technological systems has three significant effects. First, the presence of the resource structure can indicate the legitimacy of the technology. Legitimacy is interpreted as "collective recognition of, and orientation to, institutionalized and binding rules of the game" (Stryker, 1994: p. 858). The collective recognition of the resource structure enables it to generate opportunities and extend resource utilization to arenas where the resources previously did not exist. In addition, the resource structure for entrepreneurship can enable other social actors outside academia to imitate or learn the knowledge vicariously (Aldrich & Baker, 2001). As the external resources, including human and other physical resources, are included in the resource structure, the core component of the resources structure, i.e. nanotechnology, can be legitimated. Second, the resource structure is literally useful to mobilize entrepreneurial opportunities as critical resource. Not only nanotechnology itself but also human capital educated by professional programs can be considered for entrepreneurial opportunities. Romanelli & Schoonhoven (2001) argued that entrepreneurial opportunities are not ubiquitous, but rather locally identified. The local space where entrepreneurial opportunities are identified could be technological systems. The technological systems, as a resource structure, thus, enable diverse actors to interact each other and thus the local interaction leads to new organization formation. Last, technological systems can reinforce entrepreneurial opportunities by enhancing complementarities within the resource structure. As discussed, in technological systems, diverse social actors communicate, share, and develop their ideas through diverse but coherent activities. If the diverse social actors exchange resources or knowledge in terms of complementarities, the resource structure can be extensively expanded, leading to innovativeness, represented by new venture creation.

In sum, this study presents two theoretical implications. First, this study theoretically provides an element to help fill the gap which the legitimation thesis revealed to explain the phenomena of science-based community creation. By recognizing overarching structures which can integrate diverse social actors, this study illuminates the role of technological systems in the emergence of a new community. Second, the findings provide an alternative explanation to knowledge localization. The literature on knowledge localization indicates that creating relationships between social actors (especially collaboration) is a critical mechanism to explain how new knowledge is transferred across boundaries (e.g. Breschi & Lissoni, 2001a; 2001b). By emphasizing inter-organizational dependence, the argument of technological systems can supplement the salient role of collaboration in knowledge (de-)localization.

While this study has helped illuminate mechanisms in community creation, it has also some challenges that need to be addressed. First, the measurement of technological systems (i.e. depth and breadth) should be elaborated. Even though depth and breadth are theoretically orthogonal, the empirical data show they are not perfectly orthogonal. It is because system components tend to be nested across subsystems. For example, in a research center, multiple activities (such as education, industrial relations, research) can be simultaneously provided. As a research center grows, its multi-functional attributes become more apparent. Future research should address the evolution of technological systems. Second, this study minimizes the efforts for investigating the governmental efforts for technological systems. In fact, the establishment of NNI indicates that the U.S. government takes initiatives for the development of nanotechnology by awarding various kinds of research grants and other financial supports. Future research can specify how government influences the impact of technological systems on community creation.

CHAPTER 4

UNPACKING UNDERLYING MECHANISMS OF KNOWLEDGE SPILLOVER: KNOWLEDGE STREAKING, KNOWLEDGE LEAKING, RESEARCH CENTERS AND EMERGENCE OF A NANOTECHNOLOGY-BASED COMMUNITY

ABSTRACT

In this study, I specify the mechanisms underlying knowledge spillovers as they relate to the emergence of a new organizational community, derived from two or more interacting populations. I consider social structure creation to play a critical role in the formation of new organizational forms based on new technology. Specifically, when new scientific and subsequent technological breakthroughs unfold, technology is further developed by tie formation between scientists and engineers. These results in the emergence of new organizational forms dedicated to developing the technology. Empirically I investigate community emergence in organizations and populations linked by nano-science and nanotechnology in the U.S. between 1959 and 2005. I argue that the propensity of social actors to form ties with others to develop new knowledge and the propensity of others to accept new knowledge can increase the entry rate of new organizations into a nanotechnology-based community. In addition, the process of community creation is influenced by patent citation patterns and the establishment of research centers, a social structure where diverse social actors are involved in the development of new knowledge.

Keywords:

Knowledge spillover, collaboration, patent citations, community, nanotechnology

INTRODUCTION

This study seeks to understand how new knowledge created in an initial population is transferred to other populations[16], creating the conditions for emergence of a new community around a new technology shared by new firms in new populations. The evolution of scientific knowledge to commercialization has been studied in terms of knowledge spillovers. The knowledge spillover phenomena have been portrayed as “a prototypical externality, by which one or a few agents investing in research or technology development will end up facilitating other agents’ innovation efforts (either unintentionally, as it happens when inventions are imitated, or intentionally, as it may happen when scientists divulge the results of their research)” (Breschi & Lissoni, 2001a: p. 975). Griliches (1979) introduced the idea of spillover effects in developing the measurement of output in R&D intensive industries. He regarded spillover effects as ‘the effect of “outside” knowledge capital - outside the firm or industry in question – on the within-industry productivity’ (p. 102). In fact, Jaffe (1989) found that university research is positively related to corporate patents at the state level. Similarly, Zucker, Darby, & Armstrong (1998) defined knowledge spillovers as “positive externalities of scientific discoveries on the productivity of firms which neither made the discovery themselves nor licensed its use from the holder of intellectual property rights” (p. 65). That is, knowledge spillovers, originally treated as inter-firm influence of R&D spending in firm productivity, indicate that the knowledge created in universities can be transported to commercial organizations, such as firms.

[16] In this study, a population is defined as ‘the set of organizations with a particular form within a (bounded) social system’ (Hannan & Carroll, 1995: p. 29). For example, a population of universities is a collectivity of research-based institutions of higher education.

However, knowledge flows between universities and firms tend to slow within a given locale (Breschi & Lissoni, 2001a & 2001b).[17] Only co-located social actors are likely to share new knowledge and to exchange resources necessary to develop the knowledge further. For example, Jaffe, Trajtenberg & Henderson (1993) found that knowledge spillovers are geographically localized; i.e. citations to domestic patents are more likely to be domestic and more likely to come from the same state (p. 577). The conception of knowledge spillovers thus implies that localized knowledge is not easily transferred to distant locations, because there are limited resources and the requirement of deep background knowledge to develop new knowledge in a distant location (Breschi & Lissoni, 2001a & 2001b). As scientific knowledge is localized, social actors not located in the region where the knowledge is created or those who are not members of an organization based on the knowledge, find it difficult to have access to the knowledge (Boschma, 2005; Bathelt, Malmberg, & Maskell, 2004; Knoben & Oerlemans, 2006; Broekel & Boschma, 2012). In other words, through the knowledge-localization process, knowledge becomes excludable and the range of adopters is limited. By excludable, I mean that the knowledge owner can prevent others from using it (see Romer, 1990: p. s74), via typically a patent, secrecy, or trademark. Thus, knowledge excludability can prevent diverse social actors from accepting the knowledge and it discourages the integration of knowledge from diverse social actors. As a result, the more localized the knowledge, the more homogenous the populations which can apply or use the knowledge.

However, there are social mechanisms by which diverse social actors are tied to others to actively develop new knowledge. Zucker, Darby, & Brewer (1998) found that social actors involved in biotechnology (such as government and other funding agencies, universities,

[17] In this study, I posit that knowledge spillovers are not confined to only local regions; rather the locales include organizational affiliations and scientific realms as well as geographical locations.

professors, and enterprises) were connected by contractual and/or ownership ties and specifically the most productive scientists tended to collaborate with firm scientists or to be affiliated in the companies. These collaboration activities constitute a beyond-locale collectivity of social actors who engaged in the development of a common knowledge, which is usually referred to as an organizational community (Astley, 1985; Aldrich & Ruef, 2006). A community is defined as 'sets of diverse, internally homogeneous populations which depend crucially on the nature of the technologies on which the populations are based' (Astley, 1985: p. 224). In particular, when the knowledge integrating diverse social actors corresponds to scientifically specialized knowledge, the science-based community includes commercial organizations as well as academic organizations across regions (e.g. Stuart & Ding, 2006; Aldrich & Ruef, 2006; Zucker, Darby, & Armstrong, 2002; Darby & Zucker, 2005).

This is incompatible to the theoretical formulation of knowledge spillovers. Even though scientific knowledge tends to be localized, extra-locale social actors can be engaged in the development of the knowledge (Giuliani & Bell, 2005; Lee, Su, & Wu, 2010). That is, when we consider the character of knowledge (i.e. localized knowledge spillovers), it is important to understand how specialized knowledge can be integrated across organizations, populations and a community. In other words, by investigating the emergence process of a new community, we can find underlying mechanisms of knowledge spillovers which the localization thesis may not capture.

In this study, I attempt to elaborate the underlying mechanisms of knowledge spillover by illustrating the emergence of a science-based community in which diverse social actors are involved in developing and utilizing the scientific knowledge they have in common. Specifically, I emphasize that tie formation between social actors is what *creates* the structure for knowledge flow (e.g. Funk, 2014; Giuliani & Bell, 2005; Shih & Chang, 2009). Tie formation which elicits communication between two or more actors builds the basis for a knowledge spillover. In other words, by forming ties, social actors who perceive new knowledge as salient can convey or adopt this knowledge, and their actions, when aggregated, eventually lead to diffusion of the knowledge across populations to which they belong. As a result, the visibility of a novel technology can be enhanced, resource exchanges can occur, and entrepreneurs can utilize the technology for their business opportunities. Eventually, this process results in the creation of diverse commercial organizations, which organize into populations (i.e. industries). When two or more populations diversify while joined by a common technology, a community can be said to exist (Astley, 1985; Ruef, 2000; Aldrich & Ruef, 2006).

From this standpoint, I argue that tie formation can be a trigger for the creation of a new community. In particular, I specify the knowledge spillover through tie formation into knowledge streaking and knowledge leaking. Knowledge streaking is the propensity that social actors intend to disseminate their knowledge by forming direct ties with others. Since knowledge streaking unfolds when the knowledge senders take an initiative for knowledge dissemination, it is intended and sender-oriented. On the other hand, knowledge leaking is the propensity that new knowledge is transmitted from one to the other through indirect ties. Since knowledge flow is initiated only when knowledge receivers (rather than knowledge senders) take action for it, knowledge leaking is receiver-oriented. Furthermore, knowledge leaking doesn't count on whether knowledge senders are aware of the knowledge flow initiated by the knowledge receivers. As such, knowledge leaking is considered unintended from the perspective of knowledge senders. Based on this juxtaposition, this study identifies knowledge streaking and knowledge leaking in terms of knowledge creation (especially patents). That is, knowledge streaking is operationally measured based on collaboration networks (the extent to which social actors collaborate with others to create a new patent) and knowledge leaking is operationally measured based on citation networks (the extent to which social actors cite others patents to create a new patent).

Focusing on emergence of a nanotechnology-based community in the U.S., I contend that those social structures related to knowledge creation (i.e. the collaboration and citation networks) will increase the likelihood that a new community emerges. Furthermore, I illuminate the role of research centers in the community emergence process. Research centers have been understood as being which enable university scientists and engineers to jointly commercialize their knowledge (Hunter, Perry, & Currall, 2011; Clark, 2010; Sabharwal & Hu, 2013). Given that knowledge leaking is made through indirect social ties, research centers can be a vehicle to embody the indirect knowledge flow, which eventually facilitates the process between knowledge development and community creation.

This paper is organized as follows. First, I conceptualize two types of knowledge flow driven through tie formation: knowledge streaking vs. knowledge leaking. Second, based on the concepts, I hypothesize the mechanisms of knowledge spillovers in terms of knowledge streaking/leaking and research centers. With the data related to the emergence of a nanotechnology-based community between 1959 and 2005, the founding rates of new nanotechnology-based firms and the entry rates of new populations which are engaged in the development of nanotechnology are empirically estimated with respect to the hypothesized variables. Last, from the findings, theoretical and practical implications are discussed.

THEORETICAL BACKGROUND

Localization and Knowledge Spillovers

One of the most distinctive characters of a science-based community is derived from the fact that knowledge is geographically localized (e.g. Zucker et al., 1998; Jaffe et al., 1993). Localization indicates that knowledge developed from university research tends to stimulate regional economic growth (Jaffe et al., 1993). Through such a spillover mechanism, co-located social actors in a region are more likely to share new knowledge and to exchange resources necessary to develop the knowledge (e.g. Funk, 2014). In other words, as knowledge is specialized and localized, it tends to be exclusively treated and hard to be imitated (Breschi & Lissoni, 2001b). The nature of localization indicates that the knowledge exchange itself tends to be localized. The knowledge created in universities can be transported to commercial organizations, such as firms, but the knowledge flow between universities and firms is likely to happen within a locale. The localization phenomena clearly appear when the knowledge which will be potentially exchanged is tacit or specialized (Breschi & Lissoni, 2001a & 2001b). Based on the concept of knowledge spillover, Breschi & Lissoni (2001a) defined localized knowledge spillovers as "'knowledge externalities bounded in space', which allow companies operating nearby important knowledge sources to introduce innovations at a faster rate than rival firms located elsewhere" (p. 975). Similarly, Sorenson & Stuart (2001) defined geographical spillover as "a sequential entry process where new firms locate near existing firms of the same type to establish local markets for scarce inputs or to gain early exposure to knowledge produced by nearby firms" (p. 1549). The conception of spillover phenomena thus suggests that localized knowledge is not easily transferred to distant locations, especially if it is intended to be commercialized, because there are limited resources and background knowledge to develop the new knowledge in the distant locations.

Despite the growing body of research on localized knowledge spillovers, the concept of localized knowledge spillovers still remains ambiguous (Breschi & Lissoni, 2001a & 2001b). Based on the critiques of Breschi & Lissoni (2001a & 2001b), we can find three issues in conceptualization of localized knowledge spillovers. First, co-location itself may not lead to knowledge spillover. Many studies assume that knowledge externalities may well happen once social actors are co-located. It is true that co-location can enhance the possibility of face-to-face contacts between social actors or access to resources. However, many studies didn't test or prove the existence of knowledge externalities (Breschi & Lissoni, 2001a). Second, related to the lack of empirical tests, the actual knowledge transferred from universities to industries is not always specialized. Breschi & Lissoni (2001a) found that actually what local universities provide to firms was training and consultancy rather than the very knowledge the universities created. This means that "pure" knowledge spillovers many studies have conceptualized may not happen. As local universities whose reputation has increased attract many brilliant students and the students, in turn, create a localized labor market nearby, firm in that region can obtain the knowledge created in the universities through employing the students. This case, however, is not actually "pure" knowledge spillovers, which unfold through co-located social actors' interactions. In other words, no direct knowledge externality arises and the localized knowledge spillovers would be conceptually contradicted by the social actors. Further, this explains that the term of knowledge spillover can imply multiple processes in which new knowledge is transferred.

Lastly, knowledge spillovers are made not only through co-location but also through collaboration (Bathelt et al., 2004). Bathelt et al. (2004) distinguished two mechanisms of scientific knowledge transfer. There is a 'local buzz' in specialized knowledge, indicating that the knowledge is transferred only to close regions. On the other hands, knowledge can be transferred globally through collaboration. Analogously, Oinas & Malecki (2002) argued that the tendency to embrace new ideas at a focal region can be strengthened by interacting with diverse regions. These studies suggest that the knowledge exchange through collaboration doesn't always assume geographical localization. Instead, social actors can strategically collaborate with those who are not co-located in order to exchange knowledge from them. This doesn't mean that localized knowledge spillovers never happen. Rather, it reflects that localized knowledge spillovers can appear beyond the geographical boundaries. In other words, knowledge itself can be split over to the co-located firms or industries, but also it can strategically flow to the firms or industries in other locales. In this sense, the concept of knowledge spillover can be expanded with the inception of social actors' strategic behavior.

Tie Formation in Knowledge Spillover

To explain social actors' strategic behavior for knowledge spillovers, I illuminate that social ties can reflect a wide range of collaborative activities. Social actors tend to make ties with those who are even distantly located to develop new knowledge. Owen-Smith & Powell (2004) argued that knowledge can be transferred through formal inter-organizational networks. Specifically, they showed that the spillovers of biotechnology in the Boston metropolitan area resulted from proprietary alliances among biotechnology firms. The concept of tie formation in prior literature has been linked to risk-taking behavior (Baum et al., 2005), uncertainty control issues (Pfeffer & Salancik, 1978), resource mobilization (Eisenhardt & Schoonhoven, 1996; Kogut, 2000; Ozcan & Eisenhardt, 2009), and dynamic social network analysis (Greve et al., 2010; Bae, Wezel, & Koo, 2011). That is, most tie-formation studies consider tie formation as an organizational outcome (e.g. Ahuja, 2000). However, knowledge derived from tie formation tends to diffuse to potential collaborators, and tie formation, in turn, can be a smallest unit of an emergent network structure, a necessary ingredient for knowledge spillover. This suggests that tie formation is not only an organizational outcome, but also a precursor to macro-level outcomes, such as knowledge spillover and community creation. For example, Gulati et al. (2010), adopting a social construction perspective, examined how tie formation, especially bridging ties, influenced the creation and evolution of small-world networks.

To discern the enactment character of knowledge spillover, it is necessary to specify tie formation patterns as to whether a tie formed is intended or not. There are two behavioral aspects of tie formation. First, social actors who control new knowledge may intentionally seek to form ties to others anticipated to positively respond to the knowledge. Second, those who desire the new knowledge may also intentionally connect to those who control the relevant knowledge. That is, social actors can acquire critical resources not owned or which they cannot generate through tie formation (Kogut, 2000). These differentiated processes around tie formation suggest that knowledge transmission can be distinguished depending on who takes initiatives. Accordingly, by specifying the social structures built through tie formation, we can understand how new knowledge is transferred among social actors within and across regions, which eventually leads to knowledge spillover.

Knowledge Streaking vs. Knowledge Leaking

Based on the behavioral aspects of tie formation, two different types of knowledge flow are identified: *knowledge streaking* and *knowledge leaking*. *Knowledge streaking* is understood as the intended dissemination of new knowledge. Actors involved in knowledge streaking try to frame new knowledge as a paradigm and they make efforts to attract others who may potentially adopt their knowledge paradigm. Through knowledge streaking, social actors may acquire reputation, becoming known as a star scientist for example. Knowledge disseminated through knowledge streaking is codified in publications (scientific articles or patents). Accordingly, the direction of knowledge flow is outward by sending or pushing new information. Social actors who initiate knowledge streaking are mostly elites, professionals, cultural/institutional entrepreneurs or previously high status social actors (e.g. DiMaggio, 1982; Galaskiewicz, 1997). At the organizational level, knowledge streaking is related to the mechanisms by which organizations follow a knowledge developed by professional organizations (e.g. DiMaggio, 1982). As DiMaggio & Powell (1983) noted (p. 152), professional networks, such as professional and trade associations, can be a vehicle for the definition and promulgation of new knowledge to be diffused extensively. For example, DiMaggio (1982) illustrated that the role of voluntary associations, such as the Handel and Haydn Society or the Harvard Musical Association, was crucial in constructing "high" culture, as oppose to popular culture (p. 37). Knowledge streaking is also illustrated by technological innovation. For example, open source computer programs[18] function to offer computer programs free of charge to disseminate the knowledge rapidly, which can unleash knowledge streaking.

[18] "Open source" started as a social movement among computer programmers who were dispirited by Microsoft Corporation's ownership and control of a substantial proportion of the computer programming market. Individuals began constructing programs openly on the web (open = no sole ownership and multiple contributors who have no

In contrast, *knowledge leaking* is understood as knowledge transferred through secondary paths. Ahuja (2000) contends that shared assets created by collaboration can be accessed by other organizations without separating the assets from the original firm. This leads to induced inter-organizational linkages. Whether or not owners of the original knowledge intend to disseminate their knowledge, knowledge can be diffused through knowledge leaking. Actors who benefit from knowledge leaking may try to mimic new knowledge. They may also obtain survival advantages in competitive environments or enhance their performance. Knowledge obtained through knowledge leaking can be conceptualized as the translation or adoption of new knowledge. Accordingly, the direction of knowledge diffusion is backwards whereby recipients receive or pull the new knowledge. Those who initiate knowledge leaking are primarily second movers or anyone without the original knowledge in a population. At the organizational level, knowledge leaking is related to mimetic isomorphism, whereby organizations mimic others for example by following best practices culled from others. Technologically, knowledge leaking refers to the adoption of an innovation.

In addition, we can differentiate network structures characterized by knowledge streaking and knowledge leaking. Knowledge developed through knowledge streaking is understood by how new ties from those who own the original new knowledge are formed. Knowledge leaking influences the number of collaboration ties across different sectors or populations or organizations. In other words, while knowledge streaking shows intended and direct ties, such as collaboration and apprenticeship, knowledge leaking indicates unintended and indirect ties, such as citation and licensing. Based on the different patterns of tie formation, knowledge streaking and leaking have different network consequences. Knowledge streaking may be channeled

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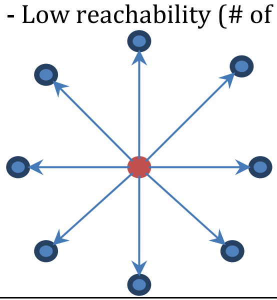
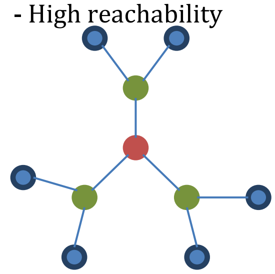
ownership rights), such that others could contribute computer code to them via the web. This resulted in the fast build and fast dissemination of such programs, plus thousands of programmers were able to proof read and improve the code as it developed. See the GNU project launched in 1984 (www.gnu.org) through a “star” network, whereas knowledge leaking is followed by “snowflake” network (See Table 1). The “Star” network has high centrality in the originating social actor but low reachability in the entire network structure. For example, DiMaggio (1982) illustrated the structural position of cultural entrepreneurs as ‘lone, centrally located’ (p.46). To disseminate the idea of high culture, i.e. for knowledge streaking, cultural entrepreneurs tend to have various ties to multiple social groups to support the idea. On the other hands, knowledge leaking manifests “snowflake” networks. Since knowledge leaking unfolds only when codified knowledge exists, the ties between social actors should be made through the knowledge. Accordingly, “snowflake” networks have low centrality, but high reachability to the entire network structure.

Table 4-1 summarizes the comparison between knowledge streaking and knowledge leaking.

TABLE 4-1: KNOWLEDGE STREAKING VS. KNOWLEDGE LEAKING

	Knowledge Streaking	**Knowledge Leaking**
Definition	Intended dissemination of new knowledge	Knowledge transfer through secondary paths
Action	Framing new paradigm	Mimicry (vs. defense mechanisms)
Benefit	Reputation (first mover advantages)	Survival or performance enhancement
Organizational change	Professional organizations formed (e.g. center for nanotechnology)	Mimetic isomorphism
Knowledge creation	Codification	Translation or Theorization
Direction of diffusion	Sending / Pushing	Receiving / Pulling
Technology domain	Technology innovation	Technology adoption
Actors	Elites / professionals / star scientists	Second movers / disciples of star scientists
Development	Increasing direct ties (mentorships or collaborators)	Increasing indirect ties (favorable bystanders or adopters)
Network utilization	Forming new ties	Utilizing existing knowledge
Network typology	**"Star" Network** - High centrality - Low reachability (# of steps) 	**"Snowflake" network** - Low centrality - High reachability 

HYPOTHESES

Knowledge Streaking and Emergence of a Science-Based Community

In explaining the emergence of a community, I argue that knowledge streaking is an important mechanism. In particular, in a science-based community, knowledge streaking can be distinguished in terms of scientific collaboration. Through co-authorship or co-inventorship, collaboration creates a social structure between authors and their affiliated organizations through scientific articles and patents (e.g. Lee et al., 2010; Ahuja, 2000; Powell et al., 2005; Singh & Fleming, 2010; Oliver, 2009). Zucker, Darby, & Armstrong (2002) found that joint research between star scientists and firm scientists leads to university-firm technology transfer for breakthrough discoveries. Collaboration, accordingly, helps a population define new knowledge, which can be a condition for the emergence of new organizations based on the knowledge.

Meanwhile, social actors collaborating for knowledge creation can differently maneuver the knowledge. Some scientists tend to focus on advancing the knowledge; others pay more attention to dissemination of the knowledge. This will differentiate the ways to codify, coordinate and reproduce the knowledge for next research. As the ways to utilize the prior knowledge are differentiated by diverse scientists, the differentiated activities for the knowledge will facilitate establishment of various organizational forms. In particular, if collaboration for knowledge development occurs between different populations, this will increase the number of populations who accept the feasibility of the new knowledge. As a result, knowledge streaking can lead to population differentiation within a community based on the new knowledge. Thus, I hypothesize:

H_{1a}: Knowledge streaking will increase the founding of new firms based on new knowledge.

H_{1b}: Knowledge streaking will increase population differentiation.

Knowledge Leaking and Emergence of a Science-Based Community

New knowledge is channeled not only by collaboration among inventors, but it also diffuses by vicarious learning (such as reading articles or imitating others' work). The literature on knowledge spillover holds that R&D activities or their achievement within a certain firm can "spill" over to other firms' R&D activities because "the existence of technologically related research efforts in other firms may allow a given firm to achieve results with less research effort than otherwise" (Jaffe, 1986: p. 984). Accordingly, once a technology derived from R&D activities of a firm has created an industry standard, other firms may imitate the R&D activities or adopt the standardized technology.

In a science-based community, the indirect knowledge flow (i.e. knowledge leaking) can be instantiated by citation practices. Through sourcing and digesting diverse existing knowledge, scientists can create their own knowledge, which, in turn, can be commercialized and sometimes be a critical source for entrepreneurship. Specifically, as new knowledge in certain populations is created and developed, external organizations begin using the evidence of the habitualized knowledge[19] in certain populations. In particular, the habitualized knowledge is adopted by investors or entrepreneurs for commercial purposes, new firms dedicated to the new knowledge are likely to appear.

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[19] Tolbert & Zucker (1996) defined habitualization as 'the development of patterned problem-solving behaviors and the association of such behaviors with particular stimuli' (p. 181). Based on this definition, habitualized knowledge refers to the knowledge whose utilization to achieve a goal is patterned in a population.

Furthermore, knowledge leaking will influence belief consensus developed across diverse populations. As discussed, innovators who create new knowledge tend to provide feasible justifications through publications (e.g. scientific articles and patents). The justification of the knowledge enables social actors to theorize the new knowledge (Strang & Meyer, 1993) and it is reflected in their own knowledge creation processes. As a result, knowledge leaking increases discourse supporting the feasibility of the new knowledge. The enhanced discourse enables scientists to share information or resources related to the new knowledge and thus business opportunities (Freeman & Audia, 2006; Stuart & Ding, 2006). In fact, Ruef (2000) recognized that the discourse supporting new knowledge, representing carrying capacity (p. 688), was a precursor of the emergence of a healthcare field consisting of diverse organizations. That is, the greater knowledge leaking, the more likely the emergence of new organizations which seek to utilize the new knowledge from diverse populations.

Thus, I hypothesize the relations between knowledge leaking and the emergence of new firms and populations are accordingly hypothesized.

H_{2a}: Knowledge leaking will increase the founding of new firms based on new knowledge.

H_{2b}: Knowledge leaking will increase population differentiation.

Role of Research Centers in Emergence of a Nanotechnology Community

Comparing to knowledge streaking, knowledge leaking may not directly lead to emergence of a science-based community, because the network structures based on citations (i.e. knowledge leaking) create disembodied knowledge flow (Shih & Chang, 2009). Since the disembodied knowledge flow requires additional efforts through personnel or equipment to codify new knowledge, knowledge leaking requires interventions by which the socioeconomic exchange relationships can be crystallized as organizational forms. For example, Gulati & Gargiulo (1999) postulated that new alliances based on prior alliances modify the existing network and eventually lead to the emergence of inter-organizational networks. Specifically, they argued that the inter-organizational relationships characterized with trust and rich exchange of information, i.e. embedded ties (Granovetter, 1985; Uzzi, 1997), become 'a growing repository of information on the availability, competencies and reliability of prospective partners' (p. 1440). Similarly, Oinas & Malecki (2002) found that external relations (or collaboration across distant regions) help to sustain greater and more diversified technological capabilities within a region. The diversified technological capabilities can be represented by various organizational forms and thus these will lead to the emergence of new subsystems. As DiMaggio (1991) highlighted, professional organizations play a role in coordinating and governing diverse, multiple organizations, leading to collective identity. Those professional organizations logically can exist as a product of the dissemination of nanotechnology.

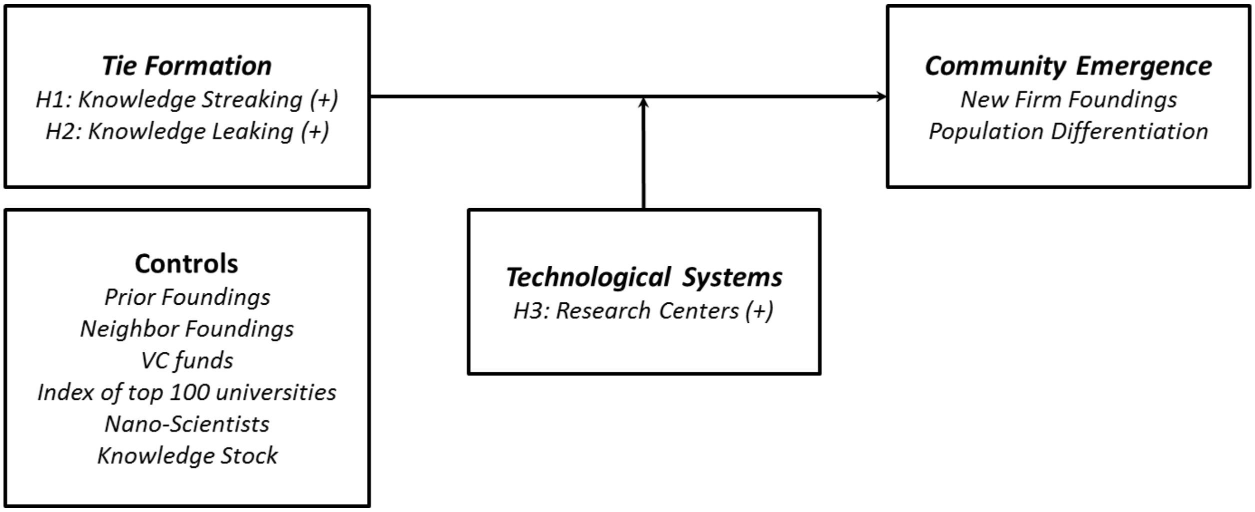
In this sense, research centers can play a role as specific organizational settings to facilitate knowledge codification (Clark, 2010; Hunter et al., 2011; Cruz-Castro, Sanz-Menéndez, & Martínez, 2012; Sabharwal & Hu, 2013; Kalinin, 2013). In prior literature, research centers have been understood as an "institutional actor at the location for innovation, production, and education and as an institutional intermediary between and among other regional actors" (Clark, 2010: p. 465). Specifically, research centers are characterized with "(1) the inclusion of an explicit goal of technology transfer, (2) an emphasis on the collaboration between academic researchers and industry with the intention of commercialization, (3) the reorientation of the research centers towards an emerging technology rather than an established industry sector, and (4) a recognition of the role of regions as engines and containers of agglomeration economies" (Clark, 2010: p. 466). Through research centers, various feedback processes, like social learning and resource exchange, unfold, and knowledge spillovers between universities and firms, in turn, can be more explicitly observed. From this standpoint, I argue that new knowledge is channeled through the intermediary organizational forms (i.e. research centers) when knowledge leaking unfolds. Yet, I conjecture that knowledge streaking will not be influenced by research centers, because the activities for knowledge streaking (i.e. collaboration) themselves signify the embodiment of the new knowledge. Therefore, I hypothesize:

H_{3a}: Research Centers reinforce the relationships between knowledge leaking and the founding of new firms based on nanotechnology.

H_{3b}: Research Centers reinforce the relationships between knowledge leaking and population differentiation.

Figure 4-1 summarizes the hypotheses proposed above.

FIGURE 4-1: SUMMARY OF HYPOTHESES



METHODS

Research Settings

To test the hypotheses, I consider the nanotechnology-based community. A community, by definition, is said to be constituted when diverse organizational forms (or populations) are involved in the commercial utilization and development of a given technology. Accordingly, in a nanotechnology-based community, several populations, such as universities, research institutes, and new companies, participate in development of nano-scale materials and products (Bonaccorsi & Vargas, 2010; Meyer & Persson, 1998; Selin, 2007). Nano-science and nanotechnology have gained increasing legitimacy as greater numbers of scientists, engineers, researchers, and entrepreneurs from diverse populations validate the feasibility of nanotechnology (Funk, 2014). Furthermore, since nanotechnology is embedded in multiple scientific realms, such as physics, chemistry, electronic engineering, material science, and life science, in the nanotechnology-based community, we can clearly identify multiple organizations based on nanotechnology from diverse populations. Thus, the field of nanotechnology is a valid research setting to study community creation.

For the empirical tests of the hypotheses related to knowledge spillover, I consider geographical aspects (e.g. Zucker et al., 1998). That is, the unit of analysis is a geographical location in the U.S. In this sense, the nanotechnology-based community can be elaborated as sets of nanotechnology-based organizations are located in geography (Freeman & Audia, 2006). The emergence of a nanotechnology-based community is, accordingly, understood by investigating creation of dedicated-nanotechnology firms in a region. As new firms are increasingly founded over time, they are likely to differentiate into several specialist populations, nonetheless still based on the same overriding science and technology base. (Aldrich & Ruef, 2006; Astley, 1985). As a result, the process of population differentiation within a community can be observed in a region as different populations emerge. With greater technical development and when two or more specialized, but related nano-populations emerge in a region, then we can speak of a nanotechnology-based community. Thus, we can identify the emergence of a community by observing whether more than a single population is created around the same technology in a region.

Building on Zucker et al. (2007) which considered "functional economic areas (i.e., central urban areas plus their suburbs and exurbs as "regions")" (p. 856), defined by the U.S. Bureau of Economic Analysis, as the units of analysis, I consider 182 functional economic areas (i.e. BEAs) to investigate how U.S. regions have commercialized nanotechnology over time. The time span of this study is between 1959 and 2005. The first date, 1959, is selected because

Richard Feynman first articulated the idea of nanotechnology theoretically. The data collection stops in 2005 due to the data availability.

Estimation Models

To test the hypotheses, the emergence of new firms and differentiated populations dedicated to nanotechnology is estimated from knowledge streaking and knowledge leaking. This study assumes that the emergence of de novo firms and differentiated populations is commonly followed by a Poisson process with the equation below:

$$\lambda_t = \lim_{\Delta t \to 0} \frac{P(t < T < t + \Delta t \mid T \geq t)}{\Delta t} \quad (1)$$

Based on this, I adopt a Cox proportional hazard model to estimate the emergence rate of new firm foundings and the hazard rate of population differentiation. To control the possible reverse causality, I use one-year lagged values of the predictors and the control variables.

Measures

Dependent variables. For the dependent variables, I consider new firm formation and population differentiation. New firm formation is measured as the number of nanotechnology-based firms founded at a given region. I identify nanotechnology-based firms as firms whose main product or technology is derived from nano-science. They include de novo firms (Schoonhoven, 2009) and de alio firms (including spin-offs or spin-outs from established organizations). For each firm, I collect its founding date and origin location. For de novo firms, I follow the collection scheme of Schoonhoven (2009). There are five criteria to discern de novo firms: (1) they should not be previously present; (2) their first product or technology is derived from nano-science; (3) they do not produce any other product or technology in any domain other than nanotechnology at founding; (4) they are private, independent start-ups; and (5) they are not organizations whose starting events were the result of mergers or former corporate divisions or business spun-off from an existing organization (Schoonhoven & Kim, 2012). As a result, 223 de novo firms were identified between 1959 and 2005. For de alio firms, I use the directories of Nanotechnology Now (www.nanotechnology-now.com). First, I list the firms which appear in the directories, and then collect the date when each firm starts developing nanotechnology-based products. For example, Ross Technologies, Inc. (founded in 1962) started developing new coating products based on nanotechnology by establishing a subsidiary, Ross Nanotechnology, Inc. in 2008. Then, the year of 2008 is coded for the entrance date of Ross Technologies Inc. From the directories, initially I find 280 nanotechnology-based firms between 1959 and 2013. To match the time frame of the other databases, I use the list of 170 firms which were founded between 1959 and 2005. With the firm collection, I code 1 for each region when one or more de novo firm is founded in a given year in the region between 1959 and 2005; 0 otherwise.

For population differentiation, defined as the extent to which subpopulations for nanotechnology are differentiated from existing populations at a given region, I consider the appearance of new populations in the community. When we identify the new firm emergence at a given region, we can also discern the firms' populations, which can be technically identified by their SIC codes. Even though the new firms are dedicated to nanotechnology, since the industrial classification for the nanotechnology industry is not formalized, the firms are classified as existing industries related to nanotechnology. Thus, through the SIC codes to which the new firm is assigned, we can measure how many different populations join the nanotechnology-based community. In other words, the populations discerned by firm foundings can indicate the events where different populations enter the nanotechnology community and the number of populations within the community refers to the degree of population differentiation. Assuming that population differentiation is initiated when two or more new populations enter the community, I code 1 when a region has the first two populations. The populations are identified with 4-digit SIC codes of de novo firms dedicated to nanotechnology between 1959 and 2005.

Independent variables. For the independent variables, knowledge streaking and knowledge leaking are measured by adopting a social network framework. Nodes in the network are defined as individuals in the collaboration and citation indices. Knowledge streaking is operationally defined as the number of collaboration ties to create a patent, and knowledge leaking is defined as the number of subsequent citations in a new patent. While collaboration ties are undirected (i.e. inventors share their knowledge bilaterally), citation ties are directed. Accordingly, we need to discern the directions of knowledge leaking. Given that a patent is based on other patents and simultaneously it can be a source of other patents, I specify the directions of knowledge leaking into inflow and outflow. The inflow of knowledge leaking indicates that social actors refer to others' knowledge (i.e. patents) in creating their own knowledge and the outflow of knowledge leaking, conversely, means that a social actor's knowledge is sourced for others' knowledge. To measure knowledge streaking and knowledge leaking, I used nanotechnology-relevant patents filed with the United States Patent and Trademark Office (USTPO) between 1959 and 2005. The nano-relevant patents are identified, based on a "keyword" search (Zucker, Darby, & Fong, 2011). According to Zucker et al. (2011), the keywords used for the classification are "any term that was prefixed with "nano" and (A) the 140 most commonly occurring noun phrases in the Virtual Journal of Nanoscale Science & Technology (VJN), (B) 297 "glossary" terms primarily derived from recommended search lists received from collaborators and advisory board members who are specialists in the field and supplemented by a web search of nanotechnology glossaries, (C) with the exception of pure measurement terms" (p. 5).

Given that knowledge streaking is operationally defined with collaboration ties among social actors, I first construct collaboration networks, from the author information of the nanotechnology-relevant patents, by year. Then, for each inventor, I count the number of collaborators for each year, which corresponds to the measure of degree centrality (Freeman, 1977; Wasserman & Faust, 1994). The degree centrality value of each inventor is aggregated to the region where he/she resides. The aggregate value of degree centrality signifies the propensity that knowledge streaking occurs within a region. That is, the greater the degree centrality, the greater the degree of collaboration involved in developing a patent; this indicates the higher likelihood of knowledge streaking.

On the other hand, the measure of knowledge leaking is based on citation networks, which refer to the relational structure made up of social actors whose patents are cited. The citation networks are constructed in two steps. First, I identify the networks of patents in terms of citations. When a patent cites another patent, knowledge of the latter patent is conveyed to the former, and this directed relation between the two patents is defined as a tie in a citation network. Assuming that the first author has the main idea in the patent and when the patent is cited, all the authors citing it accept the idea, I postulate that citing behavior results in a knowledge flow from the first author of the cited patents to all the authors to the citing patents. From the citation networks of inventors, in-degree centrality and out-degree centrality are measured to capture inflow and outflow of knowledge and aggregated by region over time respectively. To capture how new knowledge leaks, i.e. knowledge leaking, I compare the in-degree and out-degree centrality (e.g. Giuliani & Bell, 2005). That is, if knowledge outflow is dominant over knowledge inflow in a region, the region retains more inventors who can play a role of knowledge disseminators than a role of adopters. Reversely, if knowledge inflow is dominant over knowledge outflow in a region, this implies that the region has more knowledge adopters than knowledge disseminators. To capture this, I use E-I index (Krackhardt & Stern, 1998) to measure inflow and outflow of knowledge leaking as follows:

$$l_{it} = \frac{E_{it} - I_{it}}{E_{it} + I_{it}}, \tag{1}$$

where l_{it} denotes the relative dominance of knowledge leaking in region i at time t; E_{it} and I_{it} are region i's aggregated in-degree centrality and out-degree centrality at time t respectively. To discern inflow and outflow of knowledge leaking, I use a spline method. The spline equations are:

$$\begin{aligned} l_{it}^{I} &= l_{it} \quad \text{if } l_{it} > 0 \\ &= 0 \quad \text{if } l_{it} \leq 0 \\ l_{it}^{E} &= \left| l_{it} \right| \quad \text{if } l_{it} < 0 \\ &= 0 \quad \text{if } l_{it} \geq 0 \end{aligned} \tag{2}$$

Moderator. As a moderator, the establishment of research centers for nanotechnology is considered. Research centers for nanotechnology refer to the university-based organizations to develop nanotechnology, educate potential scientists, and facilitate the interactions between academia and industries (e.g. Kalinin, 2013). That is, within a research center, multiple activities related to the development of nanotechnology are sought for. Accordingly, founding research centers in a region indicates that the activities to create, reproduce, commercialize nanotechnology are institutionalized (Hunter et al, 2011; Clark, 2010). The research centers includes government funded research centers, such as Materials Research Science and Engineering Centers (MRSECs), National Nanotechnology Infrastructure network (NNIN), Centers of cancer nanotechnology (CCNEs), or any kinds of research centers which National Science Foundation (NSF) support to create and develop nanotechnology, and the research centers funded by private foundations, national labs, or state government, both of which are resided in a university. From the directories of Nanotechnology Now (www.nanotechnology-now.com), research centers were collected. Then, the founding of research centers are measured as the number of the university-based research centers featured with industrial interactions, located in each region of the U.S. between 1959 and 2005.

Control variables. First, prior foundings is the number of nanotechnology-based firms at previous time period. Density-dependence theory tells that the number of organizations in a population can signal social legitimation (Carroll & Hannan, 1989). Since this study mainly focuses on the early stage of the development of nano-science, the instances of failures of the firms are empirically rarely found. Thus, instead of using density (the cumulative number of nanotechnology-based firms), using prior foundings (as the rate of change in density) is more helpful to predict the new firm foundgins. I expect the inverted U-shaped relationships between the prior foundings and the dependent variables (new firm foungdins and population differentiation). However, at the early stage of community creation, the negative effect of prior foundings entailed by severe competition among existing firms tends to be ignorable (Schoonhoven & Kim, 2012). Accordingly, I consider a positive linear effect of prior foundings.

The density of neighbor regions is also considered as a control variable to control the effect of spatial contagion (Greve, 2002; Cattani, Pennings, & Wezel, 2003; Burt, 2010). Spatial-contagion theory deals with "how geographically delineated subpopulations grow and interact with neighboring subpopulations" (Greve, 2002: p. 847). That is, in addition to the co-located social actors, the social actors located in neighboring regions also can influence the formation of new firms as they can provide some resources for the development of nano-science or nanotechnology. Nearby regions are defined as the geographically adjacent regions of the focal region. To identify the nearby regions, I create an adjacency matrix or regions which show which regions share their borders (e.g. Greve, 2002). With the adjacency matrix, the number of nanotechnology-based firms at a given region is counted and summed by year between 1959 and 2005.

Second, financial resources are considered as a control variable in terms of resource mobilization. Financial resources available for nanotechnology-based firm births may derive from Venture Capital funds. This indicates a macro-economic condition and environmental munificence for high-technology venture firms respectively (c.f. Castrogiovanni, 1991). The greater the available funds are, the greater the likelihood of organizational foundings. VC funds are measured as the annual amount of VC funds available, which is collected from Thomson One Database (formerly VentureXpert database).

Third, whether a given region has at least one of the top 100 universities in the U.S. is also considered a control variable. Most scientific achievement is led by top universities (Darby & Zucker, 2006). As a consequence, regions with at least one of the top 100 universities are more likely to contribute to the creation of new scientific knowledge. The presence of leading universities, thus, can facilitate the emergence of a nanotechnology-based community. Since nano-science is created from a nexus of multiple scientific fields, the indicator of top 100 universities is measured in respective scientific realms. In this study, the scientific realms are categorized according to the Zucker-Darby Science and Engineering (S&E) field categorization (Darby & Zucker, 1999): (1) biology/medicine/chemistry, (2) computer/information processing/multimedia, (3) integrated circuit/semi- & super-conductor, (4) other engineering, and (5) other sciences. Using the program rankings of each field, I first create 5 dummy variables for each region, indicating whether any of the top 100 universities in each of the fields are located in a given region. Then, the dummy variables are summed and divided by 5 (the number of categories) by year. The indicator of top 100 universities, thus, ranges from 0 to 1.

Fourth, as a pool of human capital for nanotechnology, the total population of nano-scientists at a region is considered as a control variable. To identify nano-scientists, the number of Ph.D. graduates in nanotechnology from universities located in the given region is counted between 1959 and 2005. Specifically, to identify a Ph.D graduate specializing in nanotechnology, I identify whether his/her dissertation is concentrated on nanotechnology. By using ProQuest Dissertations & Theses Database[20], dissertations on nanotechnology between 1959 and 2005 are collected by using keyword search (e.g. nano*). Then, I count the number of the dissertations by region as a proxy variable for the number of nano-scientists.

Last, the stock of knowledge codified by scientists is considered, because it can be critical resources for founding firms (Zucker et al., 1998; Stuart & Sorenson, 2005; Ruef, 2005). The stock of knowledge is measured as the cumulative number of patents filed to USPTO within a region. Adopting the measurement of knowledge stock (Darby & Zucker, 2005), I assume that

[20] http://www.umi.com/en-US/products/dissertations/individuals.shtml

the contribution of the previously-developed patents decreases 20% annually. The equation for knowledge stock is shown below:

$$S_{it} = s_{it} + (1-\delta)S_{it-1}, \tag{3}$$

where S_{it} and S_{it-1} denote the knowledge stock of region *i* at time *t* and *t-1* respectively; s_{it} indicates the number of patents created at time *t* in region *i*; and δ is the depreciation rate, assumed as 0.2.

Table 4-2 summarizes the measurements of the variables described above, and Table 4-3 presents the descriptive statistics of dependent variables (i.e. new firm foundings and population differentiation), independent variables (knowledge streaking and knowledge leaking), and control variables (prior foundings/populations, VC funds, index of top 100 universities, nano-scientists, and knowledge stock).

TABLE 4-2: CONCEPTS, DEFINITIONS, MEASURES, & DATA SOURCES

Construct	Definition	Measure	Data Source
DEPENDENT VARIABLES: Emergence of Community			
New Firm Foundings	The likelihood that new firms dedicated to nanotechnology are founded in a given U.S. region	1 if two or more nanotechnology-dedicated firms appear at a region at time *t* Or, 0 if else	Schoonhoven (2009) Directories of Nanotechnology-Now (www.nanotechnology-now.com)
Population Differentiation	The likelihood that industries engaged in nanotechnology are diversified in a given U.S. region	1 if two or more two industries (two-digit SIC codes) in which nanotechnology-dedicated firms appear at a region at time *t* Or, 0 if else	Schoonhoven (2009) Directories of Nanotechnology-Now (www.nanotechnology-now.com)
INDEPENDENT VARIABLES: Knowledge Flow			
Knowledge Streaking	The extent to which inventors intend to disseminate their knowledge to others through collaboration	The total number of collaborating ties among inventors in each region of the U.S. between 1960 and 2008	USPTO Patent database Nanobank (www.nanobank.org)
Knowledge Leaking, Inflow	The extent to which knowledge is utilized by those who were not involved in its creation in a region	The total number of citing ties, relative to cited ties, among inventors in each region of the U.S. between 1960 and 2008	USPTO Patent database Nanobank (www.nanobank.org)
Knowledge Leaking, Outflow	The extent to which knowledge is sourced to those who were not involved in its creation in a region	The total number of cited ties, relative to citing ties, among inventors in each region of the U.S. between 1960 and 2008	USPTO Patent database Nanobank (www.nanobank.org)
MODERATOR: Research Centers			
Research Centers	The intensity of social entities which facilitate developing nanotechnology in a focal region	The number of research centers which appear at a region in the U.S. at time *t*	Directories of Nanotechnology-Now (www.nanotechnology-now.com)
Knowledge Transfer Activities	The variety of activities which facilitate developing nanotechnology in a focal region	The number of activities of research centers (i.e. research, education, and industrial relations) which appear at a region in the U.S at time *t*	Directories of Nanotechnology-Now (www.nanotechnology-now.com)

CONTROL VARIABLES			
Prior Foundings at a focal region	The rate of change in the cumulative number of de novo firms at a focal region	The number of firms dedicated to nanotechnology at a focal region at time *t-1*	Schoonhoven (2009) Directories of Nanotechnology-Now (www.nanotechnology-now.com)
Prior Foundings at neighbor regions	The rate of change in the cumulative number of firms at neighbor regions	The total number of (1) incumbents who firstly applied their patents dedicated to nanotechnology and (2) de novo firms at the neighbor regions at time *t-1* * neighbor regions: the areas which share boundaries of the focal region	USPTO Patent database Nanobank (www.nanobank.org)
Prior Population Differentiation at a focal region	The rate of change in the cumulative number of industries engaged in nanotechnology at a focal region	The total number of industries (2-digit SIC) appearing with firms dedicated to nanotechnology at a focal region at t-1	Schoonhoven (2009) Directories of Nanotechnology-Now (www.nanotechnology-now.com)
Prior Population Differentiation at neighbor regions	The rate of change in the cumulative number of industries engaged in nanotechnology at neighbor regions	The total number of industries (2-digit SIC) appearing with firms dedicated to nanotechnology at a focal region at t-1 * neighbor regions: the areas which share boundaries of the focal region	Schoonhoven (2009) Directories of Nanotechnology-Now (www.nanotechnology-now.com)
VC Funds	The prior investment from venture capitalists for new foundings	The total dollar amount of venture capital funds for firms dedicated to nanotechnology at a focal region at time t-1	VentureXpert (now Thomson One)
Indicator of Top 100 Universities	Whether top 100 universities in S&E field categorization (Zucker & Darby, 1999) are located in a given region	Whether the mean value of 5 dummy variables indicating whether any of top 100 universities in 5 S&E fields are located in a region in the U.S. is greater than 0.9	US-News Rankings
Nano-Scientists	The extent to which a given region bears human capital for Nanotechnology development	The number of Ph.D. graduates whose dissertation topics are involved in nano-science in a region in the U.S. at time t	ProQuest Dissertations & Theses Database & Nanobank
Knowledge Stock	The extent to which a focal region retain nanotechnology-relevant knowledge	$S_{it} = s_{it} + (1-\delta)S_{it-1}$ S_{it}, S_{it-1}: the cumulative number of patent dated to time *t* and *t-1* respectively s_{it}: the number of patent filed to USPTO at time t δ: depreciation rate (set to 0.2)	USPTO Patent database Nanobank (www.nanobank.org)

TABLE 4-3: DESCRIPTIVE STATISTICS

N=8918	Mean	SD	Min	Max	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1. New Firms Foundings	0.02	0.15	0	3														
2. Population Differentiation	0.02	0.14	0	3	0.98													
3. Knowledge Streaking	0.73	3.19	0	85.33	0.23	0.23												
4. Knowledge Leaking, Inflow	0.15	0.24	0	1	0.07	0.07	0.16											
5. Knowledge Leaking, Outflow	0.01	0.05	0	1	-0.01	-0.01	-0.02	-0.07										
6. Research Centers	0.02	0.14	0	3	0.10	0.11	0.17	0.06	0.00									
7. Knowledge Transfer Activities	0.02	0.14	0	3	0.10	0.10	0.18	0.06	0.00	0.99								
8. Prior foundings (focal)	0.01	0.08	0	1	0.11	0.10	0.11	0.06	-0.01	0.07	0.07							
9. Prior foundings (neighbor)	10.52	22.38	0	303	0.12	0.12	0.31	0.24	0.00	0.15	0.15	0.09						
10. Prior pop. differentiation (focal)	0.01	0.08	0	1	0.11	0.10	0.11	0.06	-0.01	0.07	0.07	1.00	0.09					
11. Prior pop. differentiation (neighbor)	0.19	0.66	0	10	0.10	0.11	0.22	0.12	-0.01	0.13	0.13	0.05	0.63	0.05				
12. VC funds	0.01	0.34	0	23.53	0.04	0.02	0.05	0.02	0.00	0.02	0.02	0.04	0.03	0.04	0.02			
13. Indicator of Top 100 Universities	0.05	0.12	0	1	0.02	0.02	0.01	0.03	0.00	0.04	0.04	0.02	0.02	0.02	-0.01	0.02		
14. Nano-scientists	0.81	3.90	0	82	0.13	0.13	0.20	0.11	0.00	0.23	0.24	0.12	0.14	0.12	0.15	0.09	0.24	
15. Knowledge Stock	0.22	1.15	0	22.26	0.25	0.26	0.64	0.12	-0.02	0.20	0.20	0.11	0.29	0.11	0.25	0.06	0.07	0.32

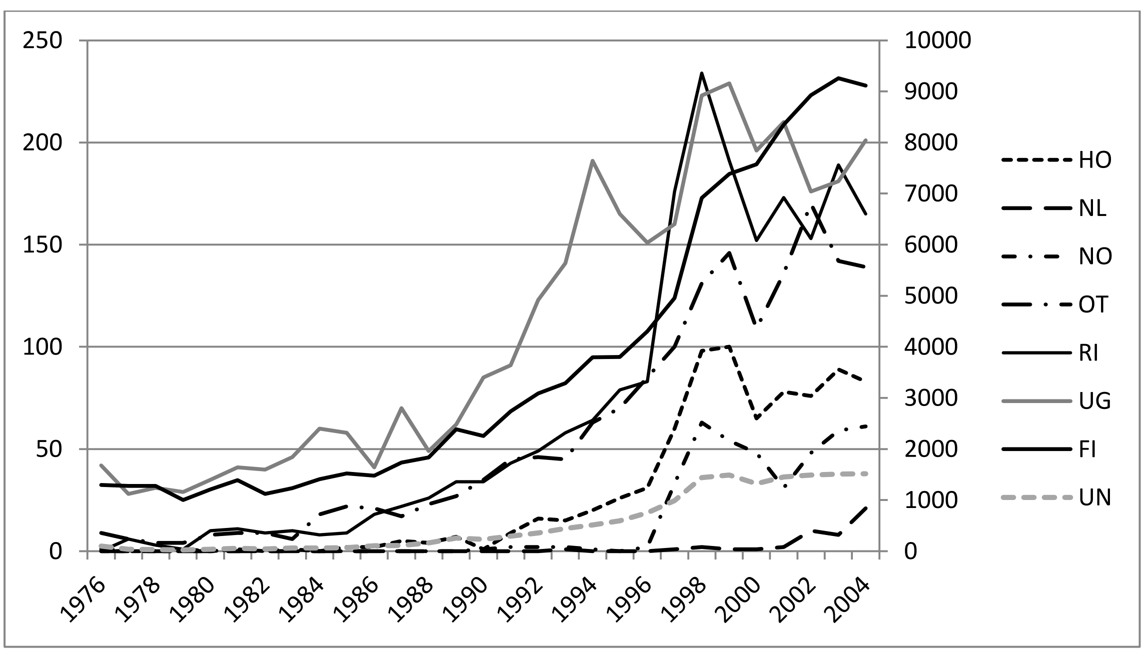
RESULTS

Emergence of the Nanotechnology-Based Community in the U.S.

In this section, we take a closer look at the emergence of new commercial organizations around nanotechnology. Figure 4-2 graphs growth in nano patents from 1976 to 2004, by organization type. Since patents have both authors (individuals) and assignee organizations (owners), we can learn how a nanotechnology community has emerged through an analysis of patents. The organization type is classified by the Nanobank database (www.nanobank.org). Organization types (assignees) have been recorded in the Nanobank data base (www.nanobank.org) and tight types are identified: firm (FI), university (UN), national lab (NL), research institute (RI), U.S. government (UG), hospital (HO), other organization (OT), and no organization recorded (NO).

Figure 4-2 shows that different organizational populations had similar patterns of patent publication over time. At an abstract level, this means that those populations have been influenced by common underlying factors and we can observe in the data three distinct periods: (1) initial creation of professional knowledge, (2) normative inducement, and (3) population-wise diffusion. In the first stage, the nano patents were granted primarily to universities and existing commercial firms. From 1976 to 1986 was the period of initial knowledge creation. Reviewing this period, several remarkable technological devices were invented. For example, the scanning tunneling microscope and the atomic force microscope were invented at IBM in 1981 and 1986 respectively, and the devices are essential to view materials at the atomic level. We can also see that between 1976 and 1986, the U.S. government was awarded the largest number of patents. This means that normatively, nanotechnology was induced by the government. With the governmental efforts, institutional changes also took place. In this period, conferences, symposiums, journals, university courses, research institutes, and PhD degrees were established (Woolley, 2007). And between 1986 and 1996, there was a surge in nanotechnology patents awarded to the U.S. government. In this second period, most organizational populations except universities increasingly were awarded nano patents. Starting in 1990, hospitals increased their otherwise non-existent patent awards. And in 1996 independent scientists or inventors without a specific organization affiliation began to patent within nanotechnology. Overall, those changes indicate that nanotechnology patents have diffused to several populations. The fewest patents were filed by national laboratories and their first patents did not appear until 1997.

FIGURE 4-2: THE NUMBER OF PATENTS GRANTED, 1976-2004, BY POPULATION



HO: Hospital, NL: National Lab, OT: Other Organizations, RI Research Institute, UG: US Government, FI: Firm, UN: University

The trajectory of scientific collaboration in nanotechnology also reveals interesting patterns. The early stage of scientific collaboration was dominated by independent populations. Firms developed their own patents and little collaboration occurred. The first inter-population collaboration was between firms and government. This can be understood as an activity of knowledge streaking, because legal issues (ownership) influence the utilization of new knowledge. Co-development of the technology can mitigate resistance to a new technology and relationships with the government can blur barriers to entry.

Knowledge Streaking/Leaking, and Research Centers, and New Firm Foundings

Table 4-4 presents the estimations of the hazard ratios of new firm foundings with respect to knowledge streaking and knowledge leaking. Model 1 represent the base model; Models 2 through 5 examines how knowledge streaking and knowledge leaking influences the founding rate of new firms; and through Models 6 through 7, I examine if the relations between knowledge streaking/leaking and new firm foundings are moderated by the number of research centers, represented by the number of research centers.

Of the models, Model 7 is the full model to test the hypotheses. In Model 7, we find that knowledge streaking is positively related to the emergence rate of new firm foundings ($\beta = .039$; $p < .01$). The estimated hazard ratios of de novo foundings with respect to knowledge streaking is 1.040 ($=e^{.039}$). The estimated hazard ratios denote the multipliers which raise the emergence rate when one unit of each predictor increases. That is, when knowledge streaking increases by one unit, the emergence rate of de novo foundings is 1.040 times greater than the base rate.

On the other hand, knowledge leaking has divergent results. For the inflow of knowledge leaking, there is a positive relation with new firm foundings ($\beta = 1.154$; $p < .001$). That is, the emergence rate of new firm foundings is 3.171 ($=e^{1.154}$) times greater than the base rate when the inflow of knowledge leaking increases by one unit. However, we cannot find any significant relation between the outflow of knowledge leaking and the founding rate of new firms.

TABLE 4-4: COX HAZARD MODELS PREDICTING NEW FIRM FOUNDINGS WITH RESPECT TO KNOWLEDGE TIES AND RESEARCH CENTERS

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
Prior Foundings (focal)	1.582*** (.369)	1.583*** (.362)	1.572*** (.363)	1.561*** (.363)	1.552*** (.350)	1.524*** (.345)	1.527*** (.348)
Prior Foundings (neighbor)	.134* (.061)	.156* (.062)	.114† (.061)	.128* (.061)	.129* (.061)	.131* (.061)	.130* (.060)
Prior Foundings^2 (neighbor)	-.064 (.068)	-.082 (.074)	-.046 (.068)	-.058 (.066)	-.057 (.073)	-.060 (.074)	-.059 (.073)
VC Funds	-.081 (.115)	-.043 (.112)	-.069 (.113)	-.060 (.113)	-.020 (.107)	-.007 (.109)	-.031 (.106)
Top 100 Universities (0/1)	-.385 (.782)	.098 (.546)	-.499 (.862)	-.281 (.782)	.096 (.630)	.024 (.670)	-.080 (.680)
Nano-Scientists	.028** (.010)	.027** (.009)	.028** (.010)	.022* (.010)	.020* (.010)	.020* (.009)	.025* (.010)
Knowledge Stock	.154*** (.025)	.073† (.038)	.155*** (.024)	.151*** (.025)	.074† (.038)	.074† (.038)	.079* (.038)
Knowledge Streaking		.041** (.013)			.039** (.013)	.043** (.013)	.039** (.013)
Knowledge Leaking, Inflow			1.261*** (.311)		1.314*** (.319)	1.307*** (.317)	1.154*** (.332)
Knowledge Leaking, Outflow			-34.73 (22.21)		-33.91 (22.23)	-33.70 (22.25)	-33.41 (21.27)
Research Centers				.479* (.209)	.453* (.203)	.617* (.252)	-.476 (.493)
Knowledge Streaking × Research Centers						-.017 (.019)	
Knowledge Leaking, Inflow × Research Centers							2.965* (1.338)
Log Likelihood	-505.71	-500.30	-499.75	-504.04	-493.05	-492.68	-491.44
AIC	1025.43	1016.61	1017.50	1024.08	1008.11	1009.37	1006.89
ΔDeviance (χ^2)	-	10.82**	11.92**	3.34†	25.32***	26.06***	28.54***

The number of BEA-year: 7,989, The number of BEAs: 182

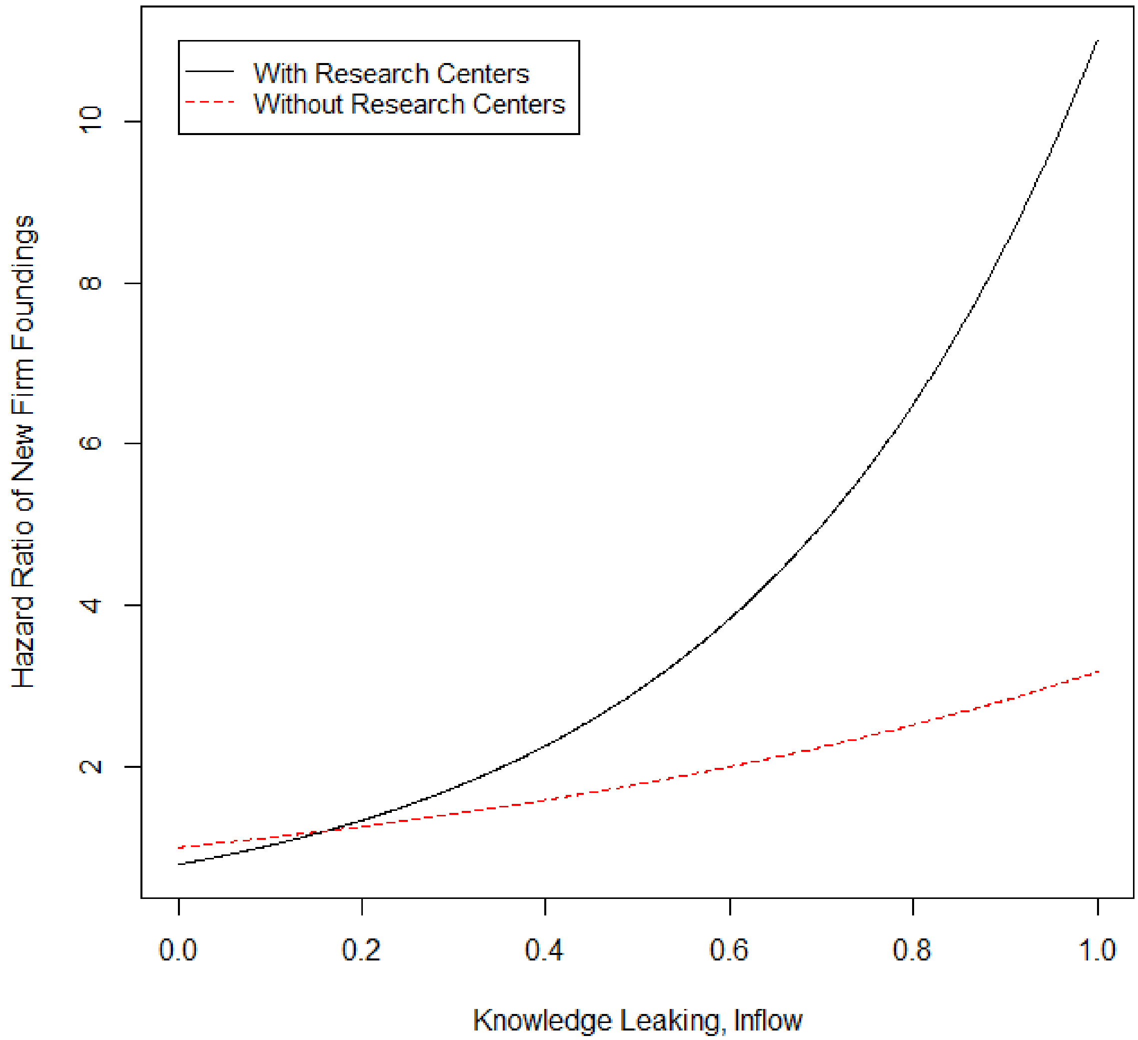
† p <.1, * p <.05, ** p <.01, *** p <.001

These results partially support Hypotheses 1 and 2. Given that the emergence rate of new firm foundings denotes the speed at which new firms are founded, these results reveal that knowledge spillover through collaboration and citation (i.e. knowledge streaking and inflow of knowledge leaking) enables entrepreneurs to consider founding a firm dedicated to nanotechnology more quickly.

In addition, we can find differentiated interaction effect of research centers and knowledge leaking. That is, from the results of Models 6 and 7, we find that the interaction term is not significantly made for knowledge streaking, but significant for the inflow of knowledge leaking. The likelihood ratio tests reveal that Model 9 is improved comparing to Model 6 (χ^2=3.22; $p<.05$) while Model 8 is not. The results mean that the knowledge flow through knowledge leaking can be crystalized by research centers in terms of commercialization. In other words, the knowledge flow through indirect ties (specifically citation) can be likely to be commercialized through research centers.

Figure 4-3 graphs the interaction effect of research centers and knowledge leaking (inflow) on the hazard ratio of new firm foundings. In Figure 4-3, regions with more research centers show a steep curve than the region with fewer research centers. Those graphs indicate that research centers can reinforce the role of knowledge leaking in the formation of new firms dedicated to nanotechnology.

FIGURE 4-3: INTERACTION EFFECT OF RESEARCH CENTERS AND KNOWLEDGE LEAKING (INFLOW) ON NEW FIRM FOUNDINGS



Knowledge Streaking/Leaking, Research Centers, and Population Differentiation

Table 4-5 presents the estimations of the hazard ratios of population differentiation with respect to knowledge streaking, knowledge leaking, and research centers. The structure of Table 4-5 is the same with Table 4-4. Through Models 2 through 5, the hazard ratio of population differentiation is estimated from knowledge streaking, knowledge leaking, and research centers independently. Models 6 and 7 specify the interaction effects of research centers and knowledge streaking/leaking on population differentiation.

For the estimation of the emergence of population differentiation, we can find consistent results. That is, as seen in Model 7, the emergence of population differentiation is positively related to knowledge streaking and the inflow of knowledge leaking ($\beta = .038$; $p < .01$; $\beta = 1.066$; $p < .001$, respectively) and the estimated hazard ratios are 1.039 ($=e^{.038}$) and 2.904 ($=e^{1.066}$) respectively. Those results, supporting Hypotheses 3, reveal that knowledge streaking and knowledge leaking (especially inflow) increases the speed of population differentiation.

Figure 4-4 depicts an interaction effect of research centers and knowledge leaking (inflow) on population differentiation. In Figure 4-4, regions with more research centers show a steep curve than the region with fewer research centers in terms of population differentiation. Those graphs indicate that research centers can reinforce the role of knowledge leaking in the differentiation of populations dedicated to nanotechnology. Therefore, it is concluded that knowledge streaking and knowledge leaking (inflow) helps speed the entry of new commercial organizational forms (including firms and industries), making the emergence of a nanotechnology-based community likely to happen. In particular, when research centers function in a region, the region can make the indirect knowledge spillover more systematic enough for commercialization.

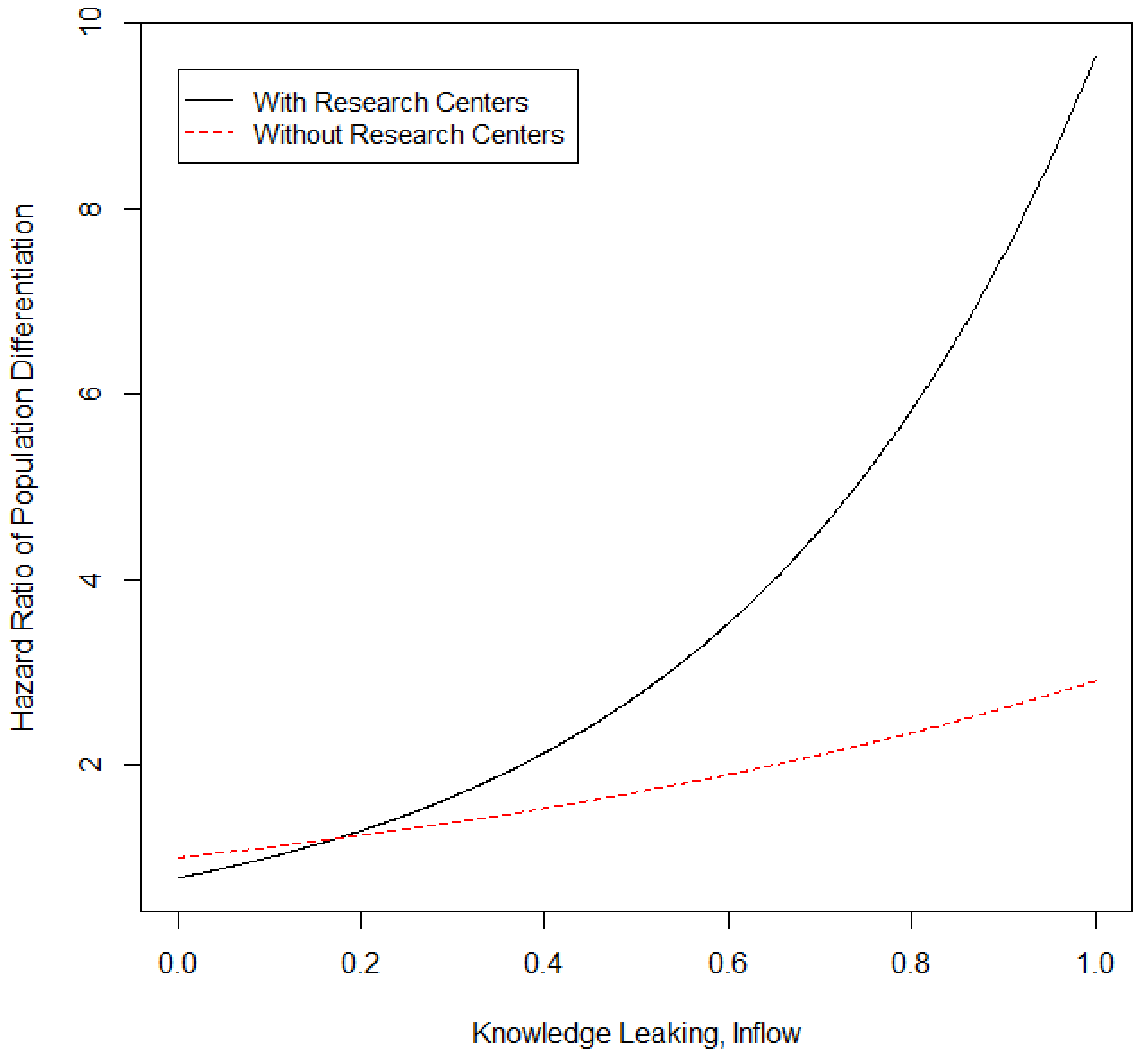
TABLE 4-5: COX HAZARD MODELS PREDICTING POPULATION DIFFERENTIATION FROM KNOWLEDGE TIES AND RESEARCH CENTERS

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
Prior Foundings (focal)	1.540*** (.387)	1.578*** (.375)	1.548*** (.381)	1.509*** (.381)	1.553*** (.364)	1.527*** (.361)	1.541*** (.359)
Prior Foundings (neighbor)	.087† (.053)	.106* (.053)	.082 (.053)	.086 (.053)	.097† (.054)	.094† (.055)	.100† (.054)
Prior Foundings^2 (neighbor)	-.031 (.036)	-.040 (.035)	-.026 (.034)	-.026 (.036)	-.031 (.035)	-.028 (.035)	-.037 (.035)
VC Funds	-.004 (.114)	.030 (.108)	-.001 (.113)	.013 (.113)	.041 (.106)	.048 (.106)	.030 (.106)
Top 100 Universities (0/1)	-.306 (.739)	.179 (.508)	-.402 (.801)	-.205 (.733)	.186 (.564)	.137 (.592)	.055 (.598)
Nano-Scientists	.029** (.010)	.028** (.009)	.028** (.010)	.023* (.010)	.022* (.010)	.022* (.009)	.026** (.010)
Knowledge Stock	.152*** (.018)	.069* (.034)	.149*** (.018)	.149*** (.018)	.066† (.034)	.067† (.035)	.068* (.034)
Knowledge Streaking		.040** (.013)			.039** (.013)	.041** (.013)	.038** (.012)
Knowledge Leaking, Inflow			1.183*** (.300)		1.223*** (.306)	1.222*** (.305)	1.066*** (.319)
Knowledge Leaking, Outflow			-5.207 (5.319)		-4.863 (5.253)	-4.809 (5.222)	-4.976 (5.288)
Research Centers				.430† (.221)	.403† (.215)	.530† (.271)	-.497 (.508)
Knowledge Streaking × Research Centers						-.012 (.016)	
Knowledge Leaking, Inflow × Research Centers							2.898* (1.372)
Log Likelihood	-508.80	-503.90	-504.40	-507.52	-498.53	-498.30	-497.04
AIC	1031.59	1023.80	1026.80	1031.05	1019.05	1020.60	1018.07
ΔDeviance (χ^2)	-	9.8**	8.8*	2.56	20.54***	21.00***	23.52***

The number of BEA-year: 8,004, The number of BEAs: 182

† p <.1, * p <.05, ** p <.01, *** p <.001

FIGURE 4-4: INTERACTION EFFECT BETWEEN RESEARCH CENTERS AND KNOWLEDGE LEAKING (INFLOW) ON POPULATION DIFFERENTIATION



As a robustness check for the moderation effect of research centers, I additionally construct a variable to capture the variety of knowledge transfer activities within a given research center. In this study, distinguishing the activities into research, education, and industrial relations, I count the number of the activities in which a given research center is involve and aggregated the number of research centers by activity in a region over time. Table 4-6 presents the moderating roles of knowledge transfer activities in the emergence of a new community. The results are found consistent with the interaction effects of research centers. That is, the activities within research centers positively moderate the relationship between knowledge leaking (inflow) and community emergence, represented by new firm foundings (Model 4) and population differentiation (Model 8).

TABLE 4-6: ROBUSTNESS CHECKS

	New Firm Foundings				**Population Differentiation**			
	Model 1	**Model 2**	**Model 3**	**Model 4**	**Model 5**	**Model 6**	**Model 7**	**Model 8**
Prior Foundings (focal)	1.572*** (.368)	1.565*** (.354)	1.545*** (.350)	1.564*** (.349)	1.521*** (.386)	1.566*** (.368)	1.550*** (.365)	1.578*** (.361)
Prior Foundings (neighbor)	.129* (.062)	.129* (.062)	.131* (.061)	.129* (.061)	.086 (.053)	.097† (.054)	.095† (.055)	.099† (.054)
Prior Foundings^2 (neighbor)	-.059 (.066)	-.058 (.073)	-.060 (.074)	-.058 (.072)	-.028 (.036)	-.032 (.035)	-.030 (.035)	-.036 (.035)
VC Funds	-.064 (.113)	-.022 (.107)	-.012 (.109)	-.034 (.106)	.009 (.113)	.038 (.106)	.043 (.107)	.028 (.107)
Top 100 Universities (0/1)	-.295 (.783)	.080 (.629)	.030 (.658)	-.091 (.680)	-.225 (.738)	.166 (.564)	.136 (.583)	.041 (.600)
Nano-Scientists	.023* (.010)	.021* (.010)	.021* (.009)	.025* (.010)	.024* (.010)	.023* (.009)	.022* (.009)	.026** (.010)
Knowledge Stock	.151*** (.025)	.074† (.038)	.074† (.038)	.079* (.038)	.149*** (.018)	.066† (.034)	.067† (.035)	.068* (.034)
Knowledge Streaking		.040** (.013)	.042** (.013)	.039** (.013)		.039** (.013)	.040** (.013)	.038** (.012)
Knowledge Leaking, Inflow		1.307*** (.320)	1.304*** (.319)	1.155*** (.331)		1.215*** (.306)	1.216*** (.306)	1.067*** (.319)
Knowledge Leaking, Outflow		-33.94 (22.17)	-33.79 (22.20)	-33.37 (21.19)		-4.900 (5.270)	-4.861 (5.248)	-4.990 (5.290)
Knowledge Transfer Activities	.420† (.236)	.392† (.233)	.544† (.291)	-.547 (.525)	.353 (.239)	.325 (.236)	.430 (.309)	-.584 (.542)
Knowledge Streaking × Knowledge Transfer Activities			-.013 (.019)				-.008 (.016)	
Knowledge Leaking, Inflow × Knowledge Transfer Activities				3.119* (1.485)				3.041* (1.545)
Log Likelihood	-504.67	-493.64	-493.41	-492.10	-508.10	-499.06	-498.95	-497.67
AIC	1025.34	1009.29	1010.82	1008.20	1032.20	1020.12	1021.91	1019.34
ΔDeviance (χ^2)	2.08	24.14***	24.6***	27.22***	1.4	19.48***	19.7**	22.26***
Obs.	7,989	7,989	7,989	7,989	8,004	8,004	8,004	8,004

The number of BEA-year: 7,989, The number of BEAs: 182

† p <.1, * p <.05, ** p <.01, *** p <.001

DISCUSSION AND CONCLUSION

This study illustrates that knowledge streaking increases the founding rates of new firms and the entry rates of diverse populations. Specifically, as for knowledge streaking, this study focuses on co-authorship in knowledge creation. The empirical findings explain that the collaboration practices, which can be interpreted as an alternative mechanism of knowledge spillover (Breschi & Lissoni, 2001a & 2001b; Zucker et al., 1998), can be crystalized into entrepreneurship, leading to the emergence of a new community. Also, I find that the inflow of knowledge leaking is helpful for new community emergence whereas the outflow is not. Since the inflow of knowledge leaking signifies the extent to which a region is likely to adopt a new knowledge, it corresponds to the mechanism of knowledge spillover previously discussed (e.g. Jaffe et al., 1993). In addition to this, this study illuminates the role of research centers: research centers amplify the positive relationships between knowledge leaking (inflow) and the emergence of a nanotechnology-based community (i.e. new firm formation and population differentiation). The finding explains that the indirect relationship between knowledge flow and entrepreneurship can be specified with the presence of research centers or their activities. Since research centers can specify the knowledge flow between universities and industries, they can facilitate the realization (or commercialization) of the new knowledge leaked from others.

Therefore, this study particularly emphasizes and specifies mechanisms of knowledge spillover in terms of tie formation. The findings in this study reveal three theoretical implications for understanding knowledge spillover. First, tie formation helps incorporate the process of knowledge spillover into an explanation of community creation. A new community can be created when diverse, multiple organizations are involved in developing common knowledge, and knowledge sharing among social actors creates knowledge spillover. In this process, tie formation within or between populations can foster inter-relationships between heterogeneous organizations, an essential characteristic of a community. That is, we can understand that the creation of social structure around new knowledge, i.e. tie formation, is a precursor of community creation.

Second, we can specify underlying mechanisms of knowledge spillovers by identifying the emergence process of a new community in terms of tie formation: knowledge streaking and knowledge leaking. Specifically, these two types of knowledge flow through tie formation provide a different view of knowledge spillovers, indicating that tie formation helps understand how innovators intend to disseminate or promote their knowledge, as well as who will be the targets for adoption of new knowledge. In particular, by considering the strategic aspects of tie formation, we can better understand how knowledge is diffused within or between populations. Third, it is found that knowledge spillovers can be achieved through interventions by which the socioeconomic exchange relationships among social actors can be crystallized as organizational forms (i.e. research centers). Specifically, research centers help facilitate knowledge spillovers when the knowledge flow is indirect and unintended (i.e. knowledge leaking). This provides another alternative explanation on knowledge spillovers. Social actors, especially entrepreneurs or existing firms which intend to adopt nanotechnology, can be suggested to utilize research centers for nanotechnology.

Even though this study provides several valid implications, it also has some opportunities to be further developed. First, its time frame can be expanded. The nanotechnology-based community is clearly identified after the establishment of NNI (National Nanotechnology Initiative) in 2001. This study considered a certain time period after the NNI establishment, but more practical implications for dedicated nanotechnology firms could be provided if the time frame covered recent years. Second, the role of research centers could be more specified. In this study, I measured research centers in terms of intensity (i.e. the number of research centers in a region). Since research centers are usually embedded in universities, other aspects of research centers, such as size, variety of activities, or other organization-specific characteristics, can be considered as factors for knowledge spillover processes. Accordingly, if we can specify the characteristics of research centers, their role for knowledge spillovers can be further specified. Third, the efforts of existing firms for knowledge spillovers could be considered. For example, the first inventions for nanotechnology were actually made by IBM for its breakthrough nano-imaging instruments. However, since IBM is an established firm, with multiple electronic, computer, and software divisions, their contributions to the nanotechnology-based community were not specified in this study. Furthermore, firm activities related to knowledge streaking or knowledge leaking, such as alliances and joint ventures, could be considered for the further understanding of knowledge spillover mechanisms.

CHAPTER 5

CONCLUSION AND IMPLICATIONS

What is not understood about new community creation? We have several helpful starting points, like Aldrich and Ruef's (2006) argument: new communities and populations emerge from the creation of new firms by entrepreneurs which, which if successful forms, proliferate into the status of a population, consisting of organizations linked by a common technology. What we do not understand are the mechanisms underlying community creation and we do not have a coherent theory of new community creation.

In this dissertation, I propose a theory of community creation whose underlying mechanisms include the interactions between academic and industrial communities. This study particularly emphasizes and specifies the role of technological systems in the process of community creation. In terms of technological systems, this study has three theoretical implications for understanding community creation.

First, technological systems help incorporate the concept of localized knowledge spillover into an explanation of community creation. A new community can be created when diverse, multiple organizations are involved in developing common knowledge, and technological systems can facilitate this process. By integrating diverse social actors, technological systems foster inter-relationships between heterogeneous organizations, an essential characteristic of a community. That is, the knowledge flow between universities and industries (i.e. knowledge spillovers) can be reinforced by the creation of the social structure around new knowledge (i.e. technological systems), which can be a precursor of community creation.

Second, collaboration as a driver of the proliferation of technological systems provides a different view of knowledge spillovers. The issues around previous studies on knowledge spillovers are that (1) knowledge spillovers are not actually tested, (2) the knowledge the universities actually provide cannot be the very knowledge the universities create, and (3) social actors intend to make coalition to create knowledge, so that the "transporting" phenomena of knowledge is not confined to only localized knowledge spillovers. This study tries to address the issues around knowledge spillovers by specifying collaboration. The collaboration-based view helps understand how innovators intend to disseminate or promote their knowledge beyond organizational and institutional boundaries as well as geographical boundaries. This study emphasizes that those cross-cutting collaborations eventually result in the creation of a new community.

Third, related to the second implication, technological systems can facilitate knowledge spillovers. In this study, two different patterns of knowledge flow through tie formation are specified: knowledge streaking and knowledge leaking. The specification of tie formation patterns indicates that tie formation can strategically differentiate patterns of knowledge diffusion. As adopters of the new knowledge increase, legitimacy of the knowledge increases. In this logic, tie formation plays a crucial role in enticing potential adopters, increasing the legitimacy of the knowledge, and technological systems can reinforce the processes.

In sum, by emphasizing the importance of technological systems, which are derived from the combination of proximal and distant scientific collaboration, as a mechanism of community creation, this study unpacks underspecified mechanisms of community creation. The multi-dimensional consideration helps derive an integrated framework to study community emergence or more broadly institutional change. Different disciplines, such as public policy, social movements, and entrepreneurship, have different explanations for the mechanisms of emergent phenomena even though the phenomena have common features. Technological systems provides not only an alternative mechanism for community creation, but also an opportunity to integrate fragmented theories from different disciplines to capture the conjecture that collaboration can lead to localized knowledge spillovers and also attract diverse organizations, including new organizational forms.

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APPENDIX A: BRIEF HISTORY OF THE U.S. NANOTECHNOLOGY COMMUNIY

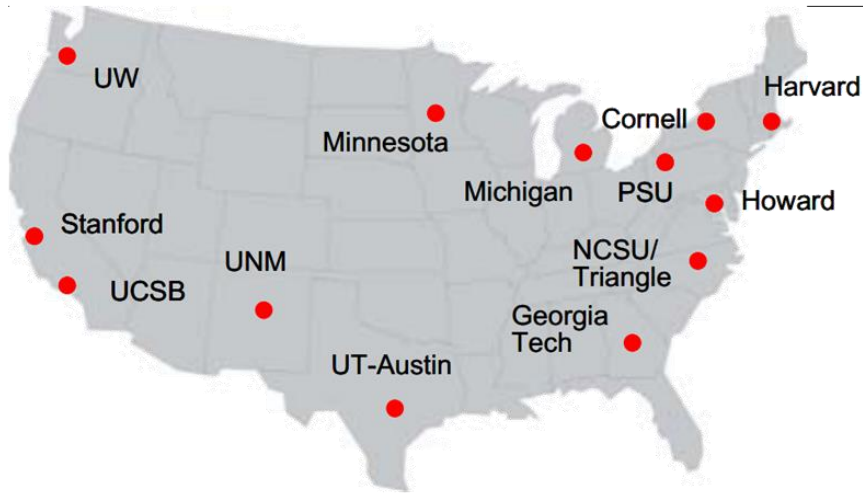
1959 First Lecture on Nanotechnology
Prof. Richard Feynman

1977 First Facilities
(Cornell, MIT)

1978 First Patent
(Rohm and Haas Company)

1981 First Instrument
Scanning Tunneling Microscope (STM)

1982 First Firm Established
Hyperion Catalysis



1994 Nanofabrication Infrastructure Established
National Nanofabrication Users Networks (NNUN)
(Cornell, Howard, Pennsylvania State University, Stanford University, and UC-Santa Barbara)

2001 Government Support Initiated
National Nanotechnology Initiative

2004 Nanotechnology Infrastructure Network
National Nanotechnology Infrastructure Network (NNIN)
(Cornell, Stanford, U. Michigan, Georgia Tech, U. Washington, PSU, UCSB, U. Minnesota, UT-Austin, Harvard, Howard, U. Washington-St. Louis, ASU, and U. Colorado-Boulder)

APPENDIX B: SCIENCE & ENGINEERING FIELD CATEGORIZATION

Table B1: Zucker-Darby S&E Field Categorization and ISI Category Descriptions

Zucker-Darby Categorization	**ISI Journal Category Description**
Biology/ Medicine/ Chemistry	Agriculture/Agronomy, Anesthesia & Intensive Care, Animal & Plant Sciences, Animal Sciences, Neurosciences & Behavior, Biochemistry & Biophysics, Biology, Biotechnol & Appl Microbiol, Cardiovasc & Respirat Syst, Cell & Developmental Biol, Oncogenesis & Cancer Res, Agricultural Chemistry, Chemical Engineering, Chemistry & Analysis, Chemistry, Cardiovasc & Hematology Res, Dentistry/Oral Surgery & Med, Dermatology, Medical Res, Diag & Treatmt, Endocrinol, Nutrit & Metab, Entomology/Pest Control, Environment/Ecology, Experimental Biology, Food Science/Nutrition, Gastroenterol and Hepatology, General & Internal Medicine, Hematology, Immunology, Inorganic & Nucl Chemistry, Clin Immunol & Infect Dis, Molecular Biology & Genetics, Microbiology, Resrch/Lab Med & Med Techn, Medical Res, General Topics, Neurology, Endocrinol, Metab & Nutrit, Medical Res, Organs & Syst, Oncology, Ophthalmology, Organic Chem/Polymer Sci, Orthopedics & Sports Med, Otolaryngology, Pediatrics, Physical Chem/Chemical Phys, Pharmacology & Toxicology, Plant Sciences, Pharmacology/Toxicology, Psychiatry, Physiology, Clin Psychology & Psychiatry, Radiol, Nucl Med & Imaging, Reproductive Medicine, Rheumatology, Environmt Med & Public Hlth, Surgery, Urology, and Veterinary Med/Animal Health
Computer/ Information Processing/ Multimedia	AI, Robotics & Auto Control, Computer Sci & Engineering, Engineering Mathematics, Info Technol & Commun Syst, and Mathematics
Integrated Circuit/ Semi- & Super-conductor	Appl Phys/Cond Matt/Mat Sci, Elect & Electronic Engn, Mechanical Engineering, Metallurgy, Materials Sci and Engn, Optics & Acoustics, Physics, and Spectrosc/Instrum/Analyt Sci
Other Engineering	Aerospace Engineering, Civil Engineering, Environmt Engineering/Energy, Engineering Mgmt/General, Geol/Petrol/Mining Engn, Instrumentation/Measurement, Nuclear Engineering, and Space Science
Other Sciences	Aquatic Sciences, Earth Sciences, and Multidisciplinary

Source: Darby and Zucker (1999).

Table B2: Zucker-Darby S&E Field Categorization & NRC Standard Doctoral Programs

Zucker-Darby Categorization	**NRC Standard Doctoral Programs**
Biology/ Medicine/ Chemistry	Biochemistry & Molecular Biology Cell & Developmental Biology Molecular & General Genetics Ecology, Evolution & Behavioral Pharmacology Chemistry Biomedical Engineering Chemical Engineering Neurosciences Physiology
Computer/ Information Processing/ Multimedia	Computer Sciences Mathematics
Integrated Circuit/ Semi- & Super-conductor	Physics Electrical Engineering Materials Science Mechanical Engineering
Other Engineering	Aerospace Engineering Civil Engineering Industrial Engineering
Other Sciences	Oceanography Astrophysics/Astronomy Statistics/Biostatistics Geosciences

Source: Darby and Zucker (1999).

APPENDIX C: PROPORTIONALITY CHECKS

Table C1: Kaplan-Meier Estimation of Hazard Ratio of Emergence of Technological Systems with Respect to Intensity and Heterogeneity of Scientific Collaboration

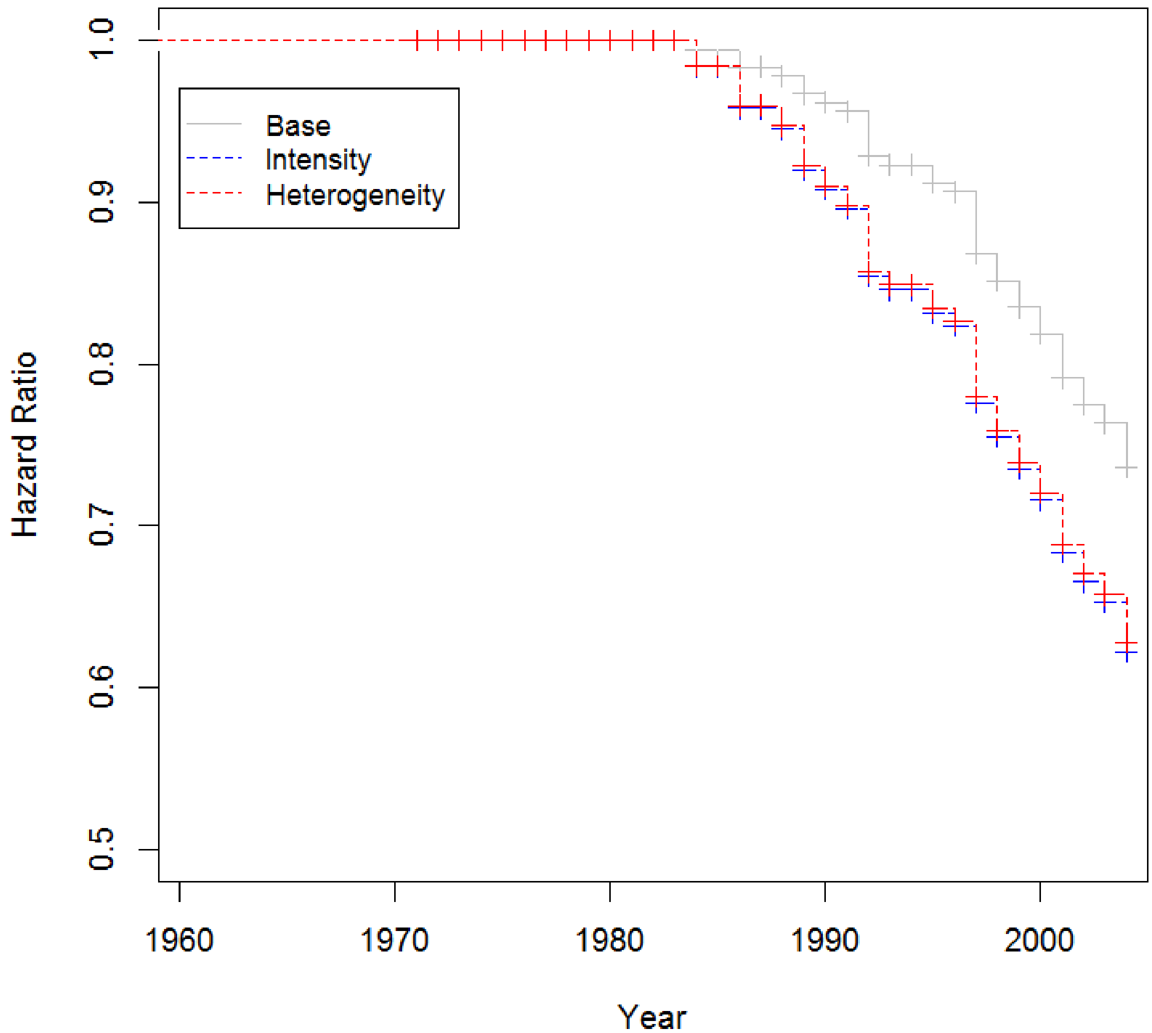
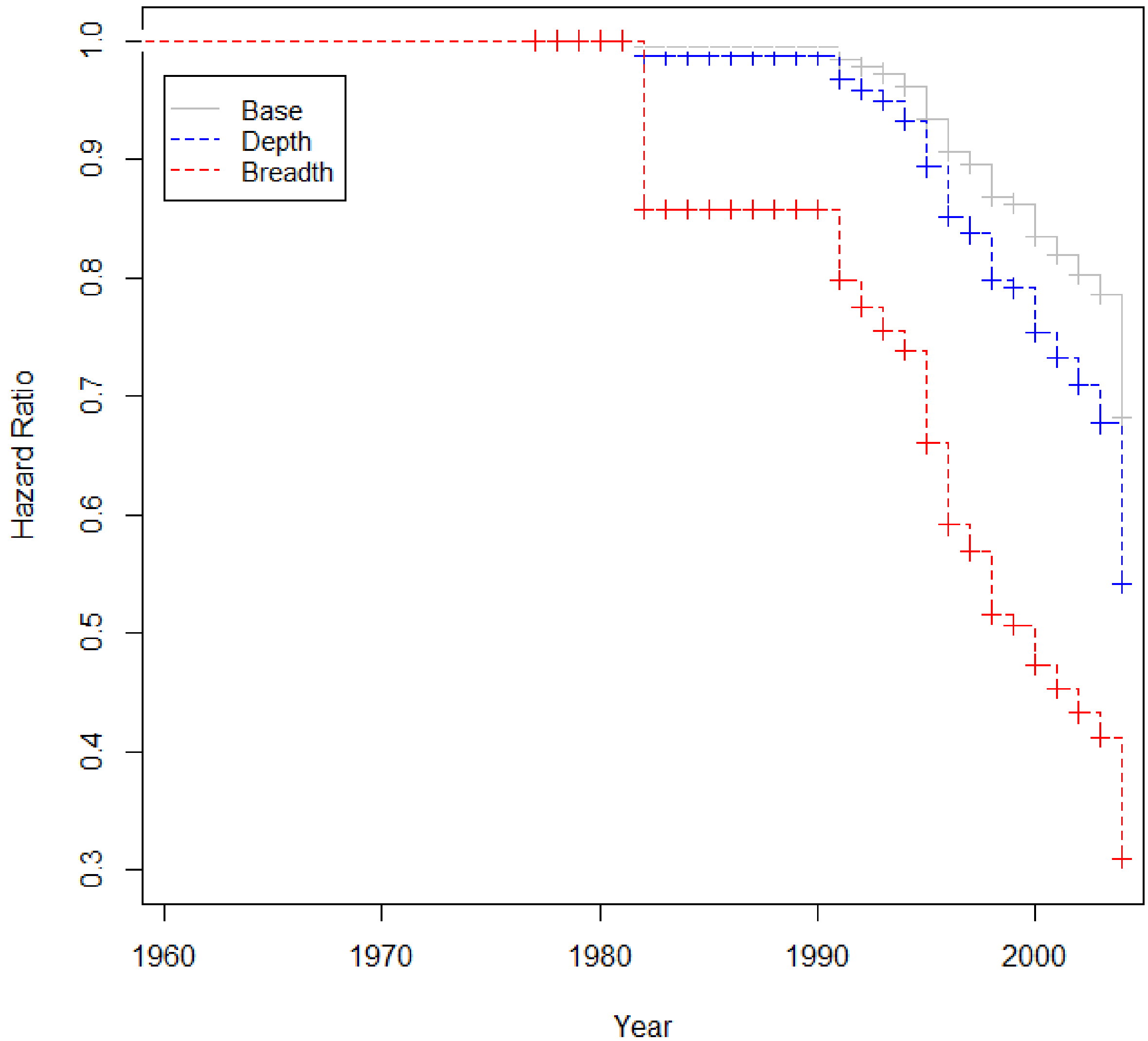


Table C2: Kaplan-Meier Estimation of Hazard ratio of de Novo Foundings and Population Differentiation with Respect to Depth and Breadth of Technological Systems



<u>Table C3: Kaplan-Meier Estimation of Hazard ratio of de Novo Foundings and Population Differentiation with Respect to Knowledge Streaking and Knowledge Leaking</u>