NANOTECHNOLOGY ENTERPRISE IN THE UNITED STATES:

STRUCTURE AND LOCATION

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NANOTECHNOLOGY ENTERPRISE IN THE UNITED STATES:

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SUMMARY

This thesis investigates the structure and location of the nanotechnology enterprise in the United States. Nanotechnology merits focus because of the high degree of innovative activity associated with it and due to its promise for regional economic development. I consider the particular sectoral and technical characteristics of nanotechnology. Building on insights from theories of high-technology industrial evolution, this thesis examines contrasting hypotheses about the location of nanotechnology firms. I find that regional academic R&D, availability of venture capital promote entry of nanotechnology firms.

CHAPTER 1

INDUSTRY LOCATION IN AN AGE OF GLOBALIZATION

In contrast to the popular opinion that advances in communication technologies and globalization will render the region inconsequential as a unit of analysis in the discussion of technology policy and economic development (Cairncross, 1997; Friedman, 2005), industry location has resurfaced as an important issue for business and public policy. Many argue strongly that the importance of regions has intensified in an age of globalization (Krugman, 1993; Florida, 1995; Audretsch, 1998; Audretsch, 2003; Bresnahan, et. al., 2004). The most apparent feature of industrial organization continues to be the concentration of firms in a few regions. While the co-location of firms is an important aspect of high-technology industries even today, however, the underlying factors that cause such behavior have changed significantly.

Scholars across several disciplines thus continue to investigate the changing subtleties and geographical patterns of the phenomenon of industry co-location. Economists emphasize the role of static and dynamic externalities. Economic geographers and urban economists emphasize the composition and dynamism of regional units. Borrowing from evolutionary theory, some scholars emphasize the role of firm birth, spin-offs, and survival.

Overall, these scholars gather substantial evidence to support the importance of knowledge spillovers. This is particularly true in the case of biotechnology industry studies. Drawing from trends and characteristics of publication and patenting activity, several studies highlight university spillovers. Comparatively under-explored, perhaps, are inter- and intra-industry spillovers. Joint ventures and alliances and markets for technology are also important characteristics of high-tech industries, and these activities also have locational implications.

Empirical studies in this area largely focus on publication and patent trends. While these trends anticipate science-driven technology enterprise, they do not provide an accurate description of the same. However, attempts have been made to describe nanotechnology enterprise and to infer locational implications from bibliometric data sources. The scale of enterprise in such studies is highly sensitive to the bibliometric definition of technology area. In addition, standards in defining technology domains using keywords are evolving. Typically, in such studies, a very large number of firms with low levels of university collaboration in academic publication activity define the industry. Patent databases, on the contrary, identify large incumbent firms and small and medium size innovative firms with high levels of inventive activity. Several studies have explored the locational implications based on geographical patterns of citations to patents. However, patents differ in economic value and only a small proportion of the patents published lead to commercial activity. Ownership of patents often changes through strategic alliances and licensing agreements. This makes the location of initial assignee and its location in the front-page of the published patent less relevant for those interested in the location of job creation. There is also considerable disagreement over the methodology used to match of patents based on patent classes and determining localization of knowledge spillovers.

This thesis is written with slightly different objectives and adopts methodologies different from those discussed earlier. My primary objective is to arrive at a conservative yet representative sample of nanotechnology enterprises and subsequently describe its structure and location. I develop databases of nanotechnology ("nano") firms from several sources. First, I develop a database of 37 firms with 'certified' market potential in the nanotechnology sector. Second, I use a sample of 205 nanotechnology spinoffs from university based researchers in the United States (U.S.). Third, I use a sample of 166 nano firms backed by private venture capital between 1996 and 2000. I also analyze the Small Business Innovation Research (SBIR) grants awarded to firms on nanotechnology related proposals.

Most studies of regional innovation choose metropolitan statistical areas (MSA) as the unit of analysis. The MSA is a core area with a large population nucleus that includes adjacent communities that have a high degree of economic and social integration with the core. However, I limit my analysis to the state level for two reasons. First, analysis at the MSA level requires allocating several thousands of data points such as publications into MSA. A few studies have focused on the most populated MSAs. Such selection methodology leaves several data points unclassified and it is also arbitrary. Second, nanotechnology policies are more actively pursued at the state level than at any other level.

Nanotechnology merits focus because of the high degree of innovative activity and the widespread belief in its promise for regional economic growth. Many states and localities have established new nanotechnology research programs and centers with the aspiration that these will foster local nanotechnology based business growth. At this early stage in the sector's development, it remains to be seen where nanotechnology enterprises will concentrate in the U.S. Analysis of the nanotechnology industry in its early stages will not only contribute to an understanding of the emerging locational characteristics of the nanotech industry, but will also to contribute to the understanding of the spatial trajectory of emerging technology in general.

Regional policy makers today focus on high-technology industry attraction and development as a regional development strategy. Such a policy design must be informed accurately of the determinants of the spatial trajectories of high-technology industry sectors. A clearer understanding of the relative effects of these factors is an important input to both policy makers and the scholarship of science and technology based economic growth.

I examine where the nanotechnology enterprise in the U.S. is located geographically. I further examine whether the distribution of nanotech firms correlates with the distribution of population or the distribution of research activity in physical sciences in the U.S. Subsequently, the role of university research in firm creation is studied. I find that 20-25% of the young firms in nanotechnology are spun off from university based research. These firms locate geographically close to the university. I find that less than 0.5% of the firms studied in the sample relocated to a different state after having originated from research activity performed in a given state. Using NSF's state-level Science and Engineering Indicators, I explore the determinants of firm entry regionally. I find that regional academic R&D and availability of venture capital promote entry of nano firms.

The thesis is organized as follows. In the second chapter, I survey the theoretical foundations for high-technology industry location. Subsequently, I review existing empirical literature on high technology areas such as biotechnology in the US.

Specifically, five categories of determinants are identified. They are a) corporate organization of R&D b) university spillovers c) inter and intra-industry spillovers d) entrepreneurial support network and public subsidy of small firms and e) firm entry and spin-offs. I conclude the chapter with several hypotheses that explain location of the nanotechnology firms. Specifically, I examine the role of university based research and entrepreneurial activity in determining the location of entry.

The third chapter provides an introduction to the rise of nanotechnology R&D activities in the US and the emergence of nanotechnology enterprise. It also considers the particular sectoral and technical characteristics of nanotechnology such as multidisciplinary and cross-sectoral nature. The development of nanotechnology is reviewed, including a focus on the role and emergence of research and enterprise development in nanotechnology (as a science-driven sector). Extant literature on nanotechnology enterprise is analyzed and contrasted with developments in biotechnology. Subsequently, the chapter provides methodology and analysis of the data on entry of firms. The final chapter of the thesis discusses the theoretical and policy implications of the findings. It also discusses the implications of firm location for public policy and economic growth.

CHAPTER 2

LITERATURE ON HIGH-TECH INDUSTRY LOCATION

Combine liberal amounts of Technology, Entrepreneurs, Capital, and Sunshine. Add one (1) university. Stir vigorously

- Gordon Moore (2004; pg 9) on the 'recipe' approach to building high-tech clusters

2.1 Introduction

This chapter presents a survey of the literature on the theory of firm and industry location in high-technology. The survey is not meant to be comprehensive; a limited but representative selection of theoretical and empirical works relevant to high technology firm and industry location theory is studied in detail. The survey aims to highlight the diversity of theoretical foundations available for modeling location problem. It also discusses the attempts to revise the existing theories in view of the developments in high-technology industries.

A theory of firm location attempts to explicate the interplay of the location choices of a firm and its performance. It views the location choice as a micro-problem specific to an individual firm. In other words, the determinants of a firm location are assumed to be endogenous to the firm. In contrast, a theory of industry location takes a broader view by recognizing that a firm's decision to locate in a particular geographical area is also influenced by the geographical distribution of other firms in related industries. I view both problems - firm location and firm co-location - as inseparable if not indistinguishable. While it is evident that inter-firm interaction costs influence the location of new firms, it is less clear whether all instances of co-location of firms are caused due to the perceived benefits of co-location. Hence, I use the terms - firm location and industry location (or, more broadly, technology business location) interchangeably in this thesis when examining both the internal and the external determinants of firm location. Any useful theory of industry location must identify both centrifugal and centripetal forces that give rise to regional dispersion or concentration of firms. Therefore, special attention will be paid to the identification of such factors.

Section 2.2 discusses new developments in economics of technological change in the context of industry location. Section 2.3 discusses the theories of economic geography connecting geography and high-technology industry. Section 2.4 discusses the work of scholars of evolutionary economists on industry location. Section 2.5 summarizes the findings nanotechnology industry location studies. Section 2.6 develops formal hypotheses.

2.2 Externalities and High-Tech Industry Location

Industry location is long known to be influenced by externalities. Marshall (1920) identified three sources of industrial localization: a pooled market for workers with specialized skills, availability of specialized intermediate inputs and services, and positive externalities of co-location. Several scholars have since improved the understanding of externalities influencing co-location. The subsequent literature falls into two categories, variously summarized as static externalities vs. dynamic externalities

(Ketelhohn, 2002) or endowment-driven vs. agglomeration-driven externalities (Alacer, 2001).

Static externalities are pecuniary in nature; that is, they are mediated by prices. They are composed of cost efficiencies that arise from favorable factor endowments and from optimization of communication, coordination, and transportation activities. The significance of static externalities is observed to be limited in high-technology industries that are primarily knowledge driven. Communication and coordination costs have been drastically reduced by advances in communication technologies. Products in high technologies such as biotechnology and information technology (such as software) are also less sensitive to transportation costs.

Perhaps the most celebrated theory of industry location based on static externalities is New Economic Geography (NEG) developed by Krugman et. al. (1998). Krugman (1991) proposes a model of production activities that suggests geographic concentration. The argument in its simplest form is as follows:

"*The basic story of geographical concentration … relies on the interaction of increasing returns, transportation costs, and demand. Given the sufficiently strong economies of scale, each manufacturer wants to serve the national market from a single location. To minimize transportation costs, she chooses a location with large local demand. But local demand will be large precisely where the majority of manufacturers choose to locate. Thus there is a circularity that tends to keep a manufacturing belt in the existence once it is established*" (Krugman, 1991: pg14).

This, the NEG theorists claim, results in a core-periphery type geographical pattern at the national level and in the localization of industrial activity at the regional level. It reinforces the three sources of industrial localization proposed by Alfred Marshall. While acknowledging the role that technology spillovers play in high-technology industries, Krugman is skeptical of their amenability to measurement and their importance as a locational determinant.

"*… high technology is fashionable, and I think we are all obliged to make a deliberate effort to fight against fashionable ideas. It is all too easy to fall into a kind of facile "megatrends" style of thought …technological spillovers play an important role in the localization of some industries, one should not assume that this is the typical reason* …" (Krugman, 1991: pg54)

On the contrary, dynamic externalities are associated with knowledge spillovers. Knowledge spillovers refer to the idea that a firm cannot fully appropriate the returns on investment in R&D. New knowledge generated from R&D is likely to benefit other firms in several possible ways. Spillovers can contribute to the R&D activities of rival firms, which leads to reduction of their production costs. Knowledge spillovers can occur within firms in a particular industry, among firms across industrial sectors, or among firms and other institutions involved in new knowledge production, such as universities and public research institutes.

Increasingly, dynamic externalities are observed to be geographically mediated. This phenomenon leads to concentration of industrial activity as firms co-locate to benefit from such externalities. Several theories of industrial location based on dynamic externalities have been proposed. They differ primarily by the type of spillovers they emphasize in the process of firm co-location.

Concentration, Diversity, and Competition

Emphasis on intra-industry spillovers leads to theories of co-location of firms within a particular industry leading to regional specialization. Here, knowledge accumulation is assumed to a result of specialization following the Marshall-Arrow-Romer framework (Romer, 1986; Romer, 1990; Bottazzi, et. al. 2003 and others). In contrast to this, the regional diversification thesis attributes greater significance to inter-industry spillovers. Knowledge accumulation is, here, assumed to be a result of the synthesis or recombination of information from interdisciplinary sources (Jacobs, 1969; von Hippel, 1998).

The debate on regional diversification vs. regional specialization is inconclusive and several studies focus on this aspect (for a review see Aydogan, 2000: pg 3). Intermediate constructs such as Porterian clusters that emphasize regional competition are also proposed and tested (Porter, 1990; Porter, 1998; Ketelhohn, 2002). Van Oort (2005) summarizes the competing hypotheses in a tabular form:

Table 2.1. Relationship of relations of agglomeration circumstances with economic growth

	Economic Growth		
Agglomeration element	MAR	Porter	Jacobs
Concentration	+	+	–
Diversity	–	–	+
Competition	–	+	+

Source: van Oort, et. al., (2005): pg 11

As shown in Table 2.1, MAR type regional knowledge specialization leads to concentration of firms in the same industry sector. In contrast, Jacobian externalities lead to diversity and competition. Porterian-type limited specialization leads to concentration and competition regionally. Empirical work on spillovers in the regional context is vast and inconclusive. A study of city level employment composition and growth by Glaeser et. al. (1992) supports diversity and competition hypothesis. Van Oort (2005) distinguishes between the relative effects of competition, diversity, and specialization on new firms and incumbents. They find that agglomeration economies within the ICT sector are stronger for new firms.

University Spillovers

Several scholars focus on universities as primary sources of knowledge spillovers and argue that this leads to regional concentration of industry around university. Jaffe (1986; 1989) explores the role of academic research in commercial innovation across the regions in the US. He finds weak evidence to suggest that an average dollar of university research would yield more spillovers in a state where both university research and industry labs are concentrated compared to those where the university research and industry labs are dispersed geographically. He also found that corporate innovation and patenting activity significantly benefits from geographically mediated spillovers from university research. In a later study, Jaffe (1993) analyzes the geographic location of the assignees of patents and other patents that cite them. He finds evidence to suggest that geographical proximity improves the likelihood of citation, that is, domestic patents in the state and in the SMSA are more likely to cite earlier patents of the same regional unit. He also observes that the localization of citations diminishes with time.

Several studies have replicated the methodology proposed by Jaffe subsequently. There is, however, considerable disagreement on the validity of this methodology. Specifically, matching citing and cited patents in a given patent class and inferring the extent of geographic localization of knowledge spillovers is disputed (Thompson, et. al.,. 2005, Thompson, et. al., 2005a; Henderson, et. al., 2005).

Even taking these criticisms into account, Jaffe's studies highlight two likely determinants of firm location. First, the location and intensity of R&D activity in academic research universities and public research institutes determine the extent of spillover benefits for local firms. In addition, the intensity of regional corporate innovation also significantly improves the prospect of spillovers. These measures capture a tendency toward co-location. Second, the time elapsed from the time of fundamental discoveries that are specific to particular industrial sectors, reduces the tendency to co-locate.

Other scholars have further explored the specific relationship between spillovers from university research and local entrepreneurial activity. Acs et. al. (1992) improve Jaffe's measure of innovation[1] and find that the role of geography in mediating spillovers might have been underestimated. They find the geographical coincidence effect to be much greater on innovative activity than on patents.

Zucker, et. al. (1996) investigate the role of university based researchers in the impact of research universities on the performance of biotechnology firms. They find evidence to suggest that the sources of spillover benefits to firms are not entirely invisible but present in firm's direct association with 'star scientists' as captured in co-authorship linkages and membership on scientific advisory boards (Zucker, et. al., 1996; Zucker, et. al., 1998; Zucker, et. al., 1998a; Zucker, 2002). Audretsch et. al. (1996a) suggest that the spatial dimension of geography is determined by the specific role played by the scientist.

[1] Jaffe (1989) used patent counts as the measure of innovation. However, Acs and Audretsch (1987) proposed an alternative measure: The number of innovations recorded in 1982 by the US Small Business Administration from the leading technology, engineering, and trade journals in each manufacturing industry.

Location characteristics of the strategic linkages among firms (Audretsch, 2003) and with academic researchers are thus an important source of evidence. In addition, such studies highlight the more direct relationships between the public and private sectors in R&D, which shapes the geography of innovation (Audretsch, 2005).

Public Private Technology Partnerships

Explicit linkages between academia and industry have been promoted since the 1980s to strengthen national competitiveness. Several policy interventions have taken place since that time: several Engineering Research Centers and Research Consortia have been established as part of an effort to promote industrial collaboration and industrial innovation. Several scholars have investigated the locational implications of such public private partnerships.

Public private partnerships lead to the development of a variety of linkages among participants. They also lead to several benefits for the industry, though measuring the extent of such benefits may be difficult (Roessner, 1998; Cohen, 2002). A survey of 355 firms involved in Engineering Research Centers revealed that geographical proximity to universities was not an important determinant of a firm's collaboration activities (Feller, 2002). However, as Feller notes, Mansfield et. al. (1996) find that firms' R&D expenditures to universities are concentrated within 100 miles of the firm location. Cohen et. al. (1996) use a similar dataset on university industry research centers and note that the relative importance of location is conditioned on the nature of R&D activities.

"*… overall, faculty research quality appears to condition industry support of university research more strongly when firms are interested in basic research, and* *location more strongly conditions this industry support when firms are interested in applied research*"

It appears that public private partnerships in certain segments of nanotechnology are more likely to be constrained by geographical proximity of industry and university linkages than others. Owen-Smith, et. al., (2004) provide a much more sophisticated analysis of contractual linkages among proximate organizations in a region. They argue that such linkages are likely to benefit spillovers effects. In addition, they argue that the organization form – practices within organizations – determine the extent of knowledge spillovers.

Public Subsidy of Small Firms

Theoretical motivation for public subsidy of small high-tech firms arises from the positive externalities associated with R&D expenditures and informational asymmetries that might preclude small firms from raising external capital (Lerner, 1999). The disbursement of such public funds can have locational implications for the spatial trajectories of high tech industries. Lerner (1999: pg 293) argues that the relative effect of public subsidy (e.g. SBIR award) may be greater in regions with concentrated populations of venture capitalists and high-technology firms. However, there is an increasing political pressure to make SBIR awards 'geographically diverse,' which some view as deviations in the program and others view as regional economic development strategies for catch-up regions.

2.3 High-Tech Industry Location and Theories of Economic Geography

Economic geographers and urban economists have developed considerable literature on industry location. This tradition's earliest theories can be characterized as endowment-driven. They regard land (and thus location) as a composite factor of production. They attempt to explain how costs of land, local labor, and transportation influence a firm's performance and, hence, its choice of location. Classical and neo-classical theories of this type formulate firm location decision as a cost minimization problem, assuming that the market location and market prices are known (for a review of such theories see McCann, 2003). Such modeling, developed in the contexts of agriculture and urban manufacturing centers, is found to be inadequate for studying high-technology industries (Malecki, 1985).

A new wave of theorizing began in the late 1960s. Such theoretical and empirical work attempted to explain location choices of several categories of business entities such as business retail outlets, manufacturing branch plants, R&D laboratories, and corporate headquarter offices. Here, I focus only on those business entities that are relevant for high-technology industries.

Location Dynamics of Industrial Production Systems

Production systems in high-technology industries are observed to have important locational implications. Scott (1982) argues that metropolitan development is dependent on local industrial production activities. He identifies several factors associated with locational concentration or dispersion of production. They include vertical and horizontal inter-firm linkages, characteristics of local labor markets such as wages; the price of land; and other immobile factors, such as local taxes (Scott, 1982a). Much of his work is motivated by the perceived decentralization of production activity away from the core of the city in the 1970s. Drawing from product-life-cycle theory, Scott argues that early phases of product development tend to take place in the inner city, which is rich in skilled labor. In later stages of product maturation, low-skilled manufacturing moves away from the inner city. He synthesizes the argument as follows:

"In recent decades, in large metropolitan regions, core areas have tended to a comparative advantage for labor intensive industrial activities, while peripheral areas have tended to have a comparative advantage for capital intensive industrial activities" (Scott, 1982).

Later, he proposes a theory of industry location based on the organizational structure of production of a firm. The proposal specifies conditions of locational convergence and divergence of plants based on efficient plant size. Taking the view that the production process is a series of transactions, he theorizes that the locational convergence of plants occurs where production processes are labor intensive, and vertically disintegrated; that is, where plants are small, outputs are highly variable in shape and form, and where interplant linkages are complex (Scott, 1983; 1983a; 1984).

Storper (1987) takes a contrary view. He argues that such vertical disintegration creates a tendency toward regional concentration of firms in a mature industry, as small specialized firms emerge with changes in technology and benefit from external economies of co-location. He studies the motion picture industry between 1960 and 1980, and observes that the number of independent productions increased from 42 (28%) to 129 (58%) over the two decades while productions by major organizations decreased from 100 (66%) to 69 (31%). This is attributed to the creation of specialized spin-offs from large integrated studios.

This locational implication of ‘flexible specialization’ has come under criticism recently, chiefly due to the questionable external validity of empirical studies set in specific industries and regions (Markusen, 2003; pg 706). That flexible specialization has several interpretations and ‘fuzzy’ conceptualizations also raises concerns. While Storper strictly refers to changes in organization of production, the real effects of technology on the tendency of a firm to flexibly specialize and consequently, to co-locate are inadequately researched. In addition, this theory of location is very narrow in its scope. It is largely production process intensive and does not accommodate the role of R&D in industry location explicitly which is an aspect central to high-technology industries. Here, technological change is assumed to be exogenous to industry location problem.

Corporate Organization of R&D and its Location

The location of a firm’s R&D operations has attracted considerable empirical attention. A study by Malecki (1979) is perhaps the first systematic survey of location of corporate R&D. The study examines the locational patterns of 330 of the largest US corporations performing R&D between 1965 and 1977. Industrial R&D continued to be a large-city activity during that period. However, a later, more in-depth study of industrial R&D revealed heterogeneity in the corporate organization of R&D and its distribution across city regions (Malecki, 1980; Malecki, 1980a, Malecki, 1980b). Malecki identifies three types of locations for corporate R&D: headquarters, production sites, and innovation centers (special locations of corporate R&D away from headquarters). He argues that R&D operations with product development emphasis are more likely to be located near production facilities, while basic research oriented towards overall corporate strategy is conducted at corporate headquarters or innovation centers. He conducted an empirical study of 58 metropolitan areas that had at least five corporate R&D laboratories in the year 1977 in order to test these conjectures. The city regions were classified based on four variables: a) the percentage of firms with headquarters which also have an R&D facility in the urban area b) the percentage of the labor force employed in manufacturing c) the number of scientists and engineers employed by the federal government, per million population, and d) the amount of R&D performed by local research universities, per million population. Discriminant analysis of the areas based on the above variables resulted in four categories of areas:

- Type 1 City: Large percentage of R&D at the firm headquarters, high percentage of manufacturing, and low levels of federal and university research
- Type II City: Large percentage R&D associated with primarily high levels of manufacturing
- Type III City: Cities characterized by university research and some federal research activity, and,
- Type IV City: Cities characterized by very high levels of university research

This is a useful characterization of regions based on R&D facilities in high-technology industries such as instruments, aerospace, and electronics products. However, less is known about the regional characteristics of emerging technology business location. It appears from Malecki's typology of cities that Type IV cities are more likely choices of location for Nanotechnology enterprise in its early phase of development.

Subsequent studies by Malecki explore the role of role of federal R&D spending (1981) and spatial heterogeneity of skilled labor (Malecki, 1985; Malecki, 1994), and forward and backward linkages of R&D intensive plants (Malecki, 1986) as determinants of locational patterns of R&D activities.

Despite significant empirical work, Malecki's studies suffer from the lack of an explicit theory of R&D location. Much of his work refers to product-life-cycle theory in its early phase and to the constructs of social networks and trust in later stages. However, no attempt is made to revise the theories to incorporate location factors.

Entrepreneurial Geography

Economic geographers have investigated the role of local entrepreneurial environment in new firm creation. Entrepreneurial environment refers to availability of venture capital, legal services, skilled and risk-taking individuals among other factors that facilitate new venture creation locally. Economic geographers have identified several locational factors that influence entrepreneurial activity and high-technology industry location are identified (Malecki, 1994; Rees, 1986; Malecki, 1985):

- scientific and engineering personnel
- local pools of venture capital
- federal R&D spending
- presence of research universities
- forward and backward linkages of R&D intensive plants
- air transportation, and,
- quality of life (urban amenities)

This list of factors is illustrative of the changing nature of the determinants - from internal determinants that are specific to firm to environmental or external determinants. Strong emphasis is given to the presence of highly skilled technical workers as an important locational determinant (Florida, 2002). Availability of venture capital is another important factor for promoting entrepreneurial activity. Kenney (2005) argues that the distribution of venture capital and the related entrepreneurial support network determine the extent of localization of high-technology industries. Powell et. al. (2002) suggest that regions where ideas and money are abundant become centers of industry location.

Other Constructs of Industry Location

Economic geography literature is replete with several other descriptive constructs of agglomerations of industrial activity. They include several variants of industrial districts, innovative milieu, technopoles, world cities, learning regions, and industrial complexes. Such constructs focus on the *processes* at work rather than on *factors*. For instance, in industrial districts the role of social trust is emphasized in the evolution of certain patterns of interaction in the industry regionally. However, it is difficult to unambiguously establish the causal relationship between proximity and trust. In addition, these constructs have questionable analytical rigor for *ex ante* analysis of firm location (for a brief discussion see Moore, et. al., 2004: pg 8). Empirical evidence gathered to illuminate some of these *processes* is also observed to be lacking in methodological rigor (Markusen, 2003). While recognizing that there are several such constructs of agglomeration, I limit my analysis to theories that identify factors explicitly.

2.4 Market Structure, Innovation, and Location

Several scholars have explored the relationship between market structure and innovation (see for a review Kamien, et. al., 1975). Since the Schumpetarian defense for imperfect competition, many scholars have investigated the relationship between firm size, innovational effort, and innovational success. Scholars interested in locational implications examined the relationship between firm size, innovation, and spillovers (Acs, et. al., 1987). While the benefits of spillovers are obvious from earlier studies, their role in new firm creation and locational implications has been less clear. Some empirical studies suggest that new firms are smaller in size. Their survival is dependent on the technology and knowledge conditions of the industry sector (Audretsch, 1991). Innovative small firms are observed to be more likely to survive. They are also observed to be the recipients of R&D spillovers from larger firms and other research institutions (Acs, et. al., 1994). Hence, the argument is that clustering of innovative activity is attributable to R&D spillovers rather than to the location of production activities in high technology industries (Audretsch, et. al., 1996). The role of large firms in innovative activities has also been investigated by several scholars. In the regional context Harrison (1994) argues that large firms remain responsible for significant proportion of innovation. In addition, the value of their innovations is observed to be more significant.

Locational implications of market structure are investigated beyond spillovers as well. There are broadly three theories of industry structure under technological change (Klepper, et. al., 1996). In the first, entry into markets is driven by innovation and the markets are characterized by low barriers to entry. Second, firms acquire a first mover advantage as dominant design emerges conferring greater benefits from process innovation. In the third, industry structure is seen as an evolutionary process. A key difference among the theories is also in their predictions of firm survival rates in pre and post-shakeout periods of technology industries.

Several corollary insights from the evolutionary theory of industry explain concentration of industrial activity geographically. First, several studies predict that first mover advantages result in the formation of oligopolies in post-shakeout periods. Subsequent industrial structure is largely determined by the spinoff activities of few early entrants. Representative studies include the concentration of the US automobile industry in Detroit (Klepper, 2002), entry by spinoffs in laser industry (Klepper, et. al., 2005), entry in US tire industry (Buenstorf, et. al., 2005). Buenstorf et. al. suggest that regional concentration of Akron tire industry in the US is a result of organizational reproduction (spinoffs) rather than agglomeration externalities.

2.5 Literature on Nanotechnology Industry

Saliency of Nanotechnology

Nanotechnology emerged as an important research area in the 1980s. From the beginning, nanotechnology has been observed to be an 'enabling', 'horizontal', and 'cross-sectoral' technology (Franks, 1987). It is projected to revolutionize several industrial sectors by providing valuable technological innovations. Applications of nanotechnology extend to several fields (see Figure 3.1, Roco, 1998; Roco[2], 2002; Roco,

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[2] Currently, Nanoscale Science, Engineering, and Technology (NEST) is chaired by Dr. Mihail C. Roco, who has been updating the scientific community on the broad trends in Nanotechnology R&D within the

2002c; Roco, 2003). For instance, in biomedical and biotechnology fields, nanotechnology can enable targeted drug delivery, gene therapy, and nanomedicine (Davis, 1997; West, 2000; Bogunia-Kubik, et. al., 2002). In the field of computing, nanotechnology can lead to nano-computers and defect tolerant computer architectures (Heath, et. al., 1998; Tseng, 2001). In the field of microelectronics, nanotechnology is set to replace silicon with carbon nanotubes – a transistor made from a large molecule (McEuen, 1998). With advances in nano-fabrication, 'ultrafast' and 'ultrasensitive' devices are now possible. There has also been significant leap in miniaturization of electronic devices (Sohn, 1998). A new field of DNA-based computing has also been opened by nanotechnology (Seeman, 1998). These advances have taken place with parallel advances in methodologies and instrumentation such as scanning tunneling microscopy (Quate, 1991).

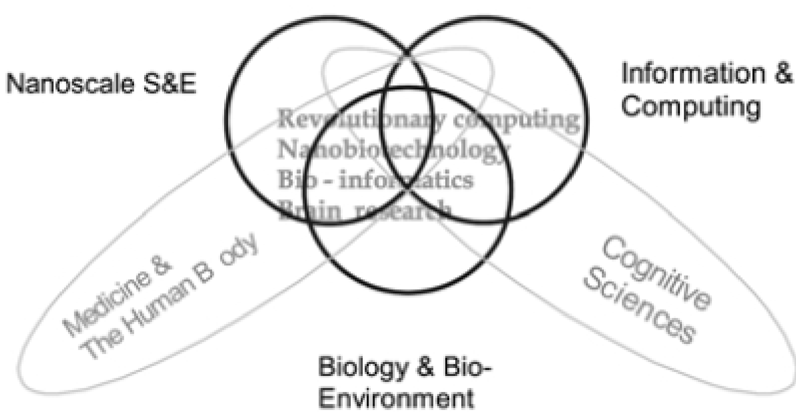

Figure 3.1: Multidisciplinary Nanoscience and Nanotechnology
Source: Roco (2002)

US and also internationally. He is an ASME fellow and also served as senior advisor for nanotechnology at the National Science Foundation's Directorate for Engineering.

Several countries, including Japan, the US, and European countries, identified nanotechnology as a national priority in early the 1990s (Malsch, 1999; Tanaka, 1999; Roco, 1998a; Roco, 2002a; Roco, 2002b). Roco (1998) observes that the federal government, large computer, chemical, and pharmaceutical companies, small and mid sized enterprises, as well as state and private foundations provide support for precompetitive nanotechnology research in the US. Federal funding for Nanotechnology R&D activity in the US has been streamlined through the creation of National Nanotechnology Initiative in 2001 (Roco, 2001b). The initiative is led by the Nanoscale Science, Engineering, and Technology (NEST) subcommittee of the National Science and Technology Council. Presently, twenty-two federal agencies participate in nano related R&D and eleven agencies have budget provisions for the nanotechnology area (NNI Strategic Plan, 2004).

It is estimated that nearly $1.1 billion was spent on nanotechnology R&D across the federal government in the US in 2005, and that close to $5billion has been spent since 2001 (NNI Budget Summary, 2006). This is more than 100% increase in budget allocation since 2001. The nanotechnology funding is organized along 7 Program Component Areas (PCA):

- Fundamental Nanoscale Phenomena and Processes
- Nanomaterial
- Nanoscale Devices and Systems
- Instrumentation Research, Metrology, and Standards for Nanotechnology
- Nanomanufacturing
- Major Research Facilities and Instrumentation Acquisition, and,

- Societal Dimension

This categorization is indicative of the evolving market segmentation of nanotechnology industry. Roco (1998; 2001) identifies several large and small firms that have established specialized groups for nanotechnology research. They include Dow, DuPont, Motorola, Lucent, Eastman Kodak, Hewlett-Packard, 3M, Mobil, Merck, Toyota, Samsung. Innovative small firms reported are Aerochem Research Laboratory and Particle Technology Inc. Table 3.1 identifies several inventions made by companies in the area of nanotechnology that have opened multi-billion dollar markets (Roco, 2001). An important aspect of developments in nanotechnology R&D is its impact on other science and engineering disciplines. Significant emphasis is given to engineering component in nanoscience education in an attempt to meet future workforce requirements (projected to be 2 million in the next 10-15 years) for the nanotechnology industry (Roco, 2002).

Table 3.1: Markets for Nanotechnology

Company	Invention
IBM	Developed magnetic sensors for hard disk heads
Eastman Kodak	Produced nano structured thin-film technologies
3M	Produced nano structured thin-film technologies
Mobil	Synthesized nano structured catalysts for chemical plants
Merck	Produced nano particle medicines
Toyota	Fabricated nano particle reinforced polymeric materials for cars (in Japan)
Samsung Elec.	Flat panel display with carbon nanotubes (in Korea)

Source: Roco (2001)

Existing Studies of Nanotechnology Industry Location

A few studies have explored nanotechnology industry location. Darby, et. al. (2003) observe the rapid growth in nanotechnology enterprise. They find that the publication activity in nanotechnology exceeds 2% of the total number of publications in science and engineering. Using a study of high-impact nanotechnology articles they argue that the nanotechnology industry exhibits a high degree of concentration geographically. Los Angeles, Santa Barbara, Silicon Valley, and Boston are found to have a high concentration of high-impact researchers. Regions with research universities such as University of Illinois at Champagne-Urbana and the North Carolina Research Triangle are also observed to be centers of research activity.

Darby, et. al. (2003) also study the 'entry' of firms in nanotechnology. They identify two sets of publications – first, they select all publications in the Institute of Scientific Information (ISI) data for 1981-1999 with 'nano' in the title and that are authored by researchers at any of the top 112 US research universities. Second, all highly cited papers in the ISI database are selected. They contend that the new knowledge in nanotechnology is highly tacit in nature and hence tends to be localized. Their regional unit of analysis is the county region in the US. The list of firms is derived from the list of author affiliations of the publications. As Darby et. al. recognize, this is a biased list of firms which excludes those that have not had co-authored publications in journals indexed by ISI. A proxy for firm entry is defined as the year of first publication in the dataset. They identify 202 firm entries, with some firms 'entering' more than once. They also record wages, employment, ranking of the doctoral programs of universities at the county level for each year. They conclude that, as in biotechnology, the top scientists spawn new firms in regions where breakthrough discoveries are made and the workforce is highly skilled. Regional venture capital is found to be an insignificant determinant.

Nanotechnology is often compared to biotechnology in relation to its similar potential to stimulate regional economic growth. Both technologies are heavily dependent on basic research for product development. Comparison of the location of biotech and nanotech industries informs the analysis of similarities in underlying factors determining location. Cortright et. al. (2002) survey 51 of the largest metropolitan areas in the US with a population of a million or more. They find that the biotechnology industry is concentrated in nine metropolitan regions in the US. Analysis of nano publications by Darby et. al. (2005) also reveals a similar set of top regions for nanotechnology (see Table 3.2).

Table 3.2 Nanotechnology and Biotechnology Industry Location.

Nanotechnology (Darby et. al., 2005)	Biotechnology (Cortright, et. al., 2002)
New York-Northern New Jersey-Long Island	Boston-Worcester-Lawrence,
San Francisco-Oakland-San Jose	San Francisco-Oakland-San Jose,
Los Angeles-Riverside- Orange County	San Diego
Boston-Worcester-Lawrence-Lowell-Brockton	Rayleigh-Durham-Chapel Hill
Washington-Baltimore	Seattle-Tacoma-Bremerton
Chicago-Gary-Kenosha	New York-Northern New Jersey-Long Island
Champagne-Urbana	Philadelphia-Wilmington-Atlantic City
Detroit-Ann Arbor-Flint	Los Angeles-Riverside-Orange County
Philadelphia-Wilmington-Atlantic City	Washington-Baltimore
Raleigh-Durham-Chapel Hill	

Source: (Darby, et. al., 2005), (Cortright, et. al., 2002)

Cortright et. al. (2002) identify two important factors in determining regional concentration of biotechnology activity – the availability of pre-commercial medical research and private investments in product development. They also observe that most biotech firms operate at a loss, spending large amounts on research and development for several years. These firms rely on venture capital investments and on research contracts and equity investments from large pharmaceutical companies. Hence, availability of local venture capital is found to be an important determinant of business location.

2.6 Research Questions and Hypotheses

In the earlier sections, we have identified several important factors that determine the location of new industries. They include corporate organization of R&D, university spillovers, industry spillovers, entrepreneurial support network and public subsidy of small firms, and firm birth, spin-offs, and survival characteristics. Given the general purpose nature of nanotechnology, the emerging industry is characterized by heterogeneity in entry pattern. We observe entry by diversification of existing firms, entry by spinoffs from university research and existing firms, and entry of new firms supported by public and private venture capital. This leads us to the following hypotheses on entry of firms in nanotechnology.

Random Entry Hypothesis H0: The locations of nanotechnology firms in the US exhibit no geographical concentration

This hypothesis suggests that the location of entry of nanotechnology firms is random. In other words, nanotechnology firms do not concentrate geographically and firms are equally likely to locate in any given regional unit of analysis such as a metropolitan statistical area. There are a wide range of economic, political and idiosyncratic reasons (such as personal preferences of decision makers in individual firms) that influence the location decision problem at the firm level in each category. This hypothesis suggests that the net effect of these factors result in no concentration of nanotechnology firms geographically. In other words, the geographical distribution of firms correlates with the population in the US; that is, regions with a larger population will have more firms and regions with less population will have fewer numbers of firms.

Path Dependent Large-firm Hypothesis H1: The location of nanotechnology firms in the US is determined by the location of large firms diversifying into the nanotechnology domain.

Literature on path dependency, industry spillovers, and evolutionary theories of industrial organization emphasize the role of local institutions in shaping the technological trajectories of regions. Large incumbent firms account for disproportionate level of R&D investments, publications, and patenting activity in nanotechnology. These institutions determine the growth of nanotechnology industry locally. This hypothesis suggests that the regions with large incumbents in other high technology areas are more likely to become the fertile locations for the entry of nanotechnology firms.

Science-driven Spillover Hypothesis H2: The location of nanotechnology firm entry in the US is determined by the intensity of scientific activity and intellectual human capital in the region.

University spillovers are a source of major innovations. Entrepreneurial activity that spawns from such innovations is more likely to exhibit robust post-entry growth. Firms spun off from academic research and commercialization efforts are more likely to locate close to universities that host researchers. Since the nanotechnology industry is still driven by major scientific inventions, it is more likely to locate near universities with significant scientific activity in nanotechnology. In addition, a corollary hypothesis implies that nanotechnology firms are more likely to locate in regions that host highly-cited academic researchers. As a corollary, we contend that nanotechnology is similar to biotechnology, as both are science and venture capital driven. Hence, they may have a similar locational pattern.

Venture Capital Availability Hypothesis H3: The location of nanotechnology firm entry in the US is determined by the intensity of venture capital available in the region for nanotechnology startup activity.

Venture capital is often cited as the missing link between invention and its commercialization. Both economic geographers and business scholars have found evidence to suggest that the geographical distribution of venture capital is concentrated in a few regions in the US. This hypothesis suggests that firm entry is highly correlated with the geographical distribution of venture capital in nanotechnology.

Policy-driven Incentives Hypothesis H4: The location of nanotechnology firm entry in the US is determined by high technology based regional economic development initiatives with a nanotechnology focus.

Several regions have explicit initiatives to promote nanotechnology at the regional level. These initiatives include increasing R&D investments in nanotechnology, building new facilities for incubation of firms, hiring eminent researchers, and providing assistance (for example, to secure grants such as SBIR awards) to commercialize innovations. This hypothesis suggests that these initiatives promote firm entry in the nanotechnology domain.

The next chapter describes the methodology adopted in the present study. It discusses definitions of nanotechnology and reviews publication and patenting trends. I then explore these five hypotheses in detail.

CHAPTER 3

ANALYSIS OF NANOTECHNOLOGY INDUSTRY LOCATION

In this chapter, I describe the methodology and analyze the locational patterns of early entrants into nanotechnology industry. Section 3.1 describes the definition of nano technology and the methodology and sampling strategy for studying nanotechnology firms. In section 3.2, I discuss trends in research and technology activity in nanotechnology. Section 3.3 conducts tests of the hypotheses proposed in chapter 2. Particularly, the role of university based entrepreneurial activity is investigated. In section 3.4, I present a regression model to predict the impact of regional research and technology measures on nanotechnology startups.

3.1 Methodology and Data Sources

Defining Nanotechnology

Earlier studies exploring nanotechnology industry defined nanotechnology using a keyword strategy. Several competing keyword based definitions exist today[3]. These strategies have been used to identify name of companies publishing and patenting in nanotechnology. Typically, such strategy results in identification of a large number of firms with small level of activity. For instance, Figure 3.8 shows the distribution of the number of firms with US patents in nanotechnology identified using search strategy proposed by Huang et. al., (2003). There are 779 firms with at least one patent in the

[3] See for instance, Huang (2003), CREA (2005)

database after the names of the companies have been cleaned for variations in spellings. We see that about 10% of the companies have on average more than one patent per year and 62% of the companies have only one patent in the six year period. Further, it is less clear if the one patent owned by a firm in the tail of the distribution is of significant economic value. Licensing of patents also leads to change in ownership of commercialization process related to the patent. Similarly, identification of firms using keyword searches on publication databases selects a large number of firms with low level of publication activity. For these reasons, I avoid keyword based search as the sole strategy for selection of firms.

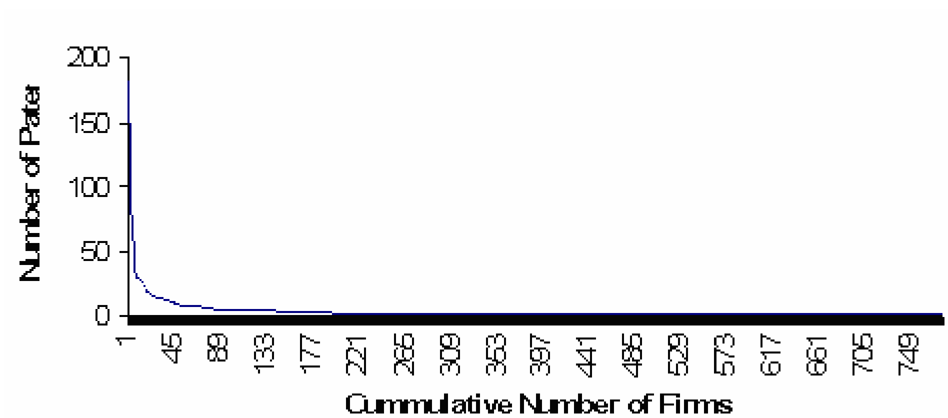

Figure 3.2 Number of US patents in nanotechnology by Firms in the US 2000 – 2004
Source: (USPTO, 2006), Author's Calculations, Nanotechnology Definition: Huang, et. al. (2003)

Sampling for Nanotechnology Firms

It has been observed earlier that close to 1000 firms are active in nanotechnology areas. Some estimate that there are close to 200 public and 700 private firms (Innovest, 2005). Several online directory listings of nanotechnology firms exist today. However, the membership in such lists is based on self-reporting and it is not based on prior validation.

Specialist Public Firms: Faced with the problem of definition and valuation of nanotechnology industry, various financial companies have identified several publicly listed firms based on intensive case studies. These firms are used to developed market indices. There are at least five nanotechnology indices present today. They are the Punk Ziegel Nanotechnology Index, International Securities Exchange – CCM Nanotechnology Index, Merrill Lynch Nanotech Index, Global Crown Capital Nanotechnology Index, and Lux Nanotech Index. While some feel that these indices are modern day marketing tools, they do serve as important market signals of their economic potential. There is, however, a general lack of consensus among these indices (for complete listing see Appendix A). These indices together, identify thirty-nine nanotechnology specialist firms and nine incumbent firms. I consider the thirty-seven specialist public firms for analysis that are located in the U.S.

Spinoffs from university based research: Second, I use a dataset of 205 nanotechnology startup firms founded by university based researchers. This listing is developed in several steps. First, nano patents assigned to U.S. universities are identified. Subsequently, individual researchers associated with each patent are identified. Companies founded by these researchers are then identified using web searches.

Nanotechnology firms supported by venture capital: Third, I use a database of nanotechnology firms supported by venture capital. There are 166 firms in this data set and they overlap with the earlier lists. The database is obtained from Venture Economics for the period 1996-2000. Data on location and stage of funding is obtained. Fourth, data on all firms supported by SBIR grants for nanotechnology related proposals is collected.

There are more than 1000 successful proposals for the period 1995-2004. There are 225 firms with more than one SBIR award during the period.

Selection Bias in the Sample

There are limitations to the chosen sampling strategy. First, the selection of firms is not random across the types of entrants. Spinoffs from existing companies are not sufficiently represented here while university spinoffs are robustly selected. Data on venture capital supported entrant firms is limited to the period 1996-2000. Data on corporate spinoffs is unavailable for the present study. The sample of specialist public firms represents highly successful firms in the industry. Data on firm exit from Nanotechnology is unavailable. In all the above cases, only certain values of the outcomes (i.e. entry) above a threshold are observed. We only observe survivor firms. We only observe those firms that are successful in acquiring venture capital funding. This limits the determination of empirical probabilities of entry. For instance, in the present study, I wish to determine the role of university research or venture capital in inducing entry of firms regionally. In other words, I wish to determine the empirical probability of a firm being supported by venture capital given that the firm is a startup in nanotechnology. However, I have data for a limited period of time on nanotechnology startups that are supported by venture capital. It is also difficult to determine the proportion of firms supported by venture capital funding in nanotechnology. In the equation below, it is difficult to obtain point estimates for the terms on the right hand side, without random sampling or study of population of nanotech firms.

$$\Pr\left(VC\ funded \mid Nanotech\,Startup\right) = \frac{\Pr\left(VC\ funded, Nanotech\,Startup\right)}{\Pr\left(Nanotech\,Startup \mid VC\,funded\right)}$$

While it is desirable to have a comprehensive database of startup and incumbent firms in nanotechnology, creation of such a database is difficult and expensive for several reasons discussed earlier. There is also no reason to believe that the sample of firms selected in the present study is a random sample. In addition, there is the issue of firm survival. Successful entry is characterized by strong post entry growth. While it is common to measure post entry growth in terms of the annual increase in firm size and sales, such information is difficult to gather for many small private startup firms in nanotechnology. Hence, the counts of entry by location examined in the study suppress the underlying heterogeneity in characteristics of the entrants. However, at this stage of the nanotechnology industry, empirical studies are constrained by these limitations. While definitive causal inference may be difficult to establish, empirical regularities in industry structure and location can be observed from the sample. The sample of firms developed here allows for study of such regularities, especially in academic entrepreneurial activity in nanotechnology.

Characteristics of Nanotechnology Specialist Public Firms

As noted earlier, there are 37 U.S. firms with primary operations in nanotechnology. Table 3.3 presents a detailed description of the NAICS industry classification. The sample of firms is dominated by two sectors – electronics and pharmaceuticals. In addition, several firms engage in developing intermediary products that enable further research. For instance, several firms engage in developing instrumentation that enables research and precision measurement at the nano level. Other firms manufacture materials that are intermediary research inputs such as chemical products (inorganic dye and pigment) or nanotubes.

In addition, there are nine large incumbents in related industries diversifying into nanotechnology. These incumbents account for a large proportion of research and technology activity in nano. Corporate organization of R&D in these firms has locational implications for the spatial trajectories of nanotechnology industry. However, this aspect is not explored in the present study. The next sections draw on the definitions and data sources discussed above.

Table 3.3 NAICS Industry classification of Select Nanotechnology Public Firms

4Digit NAICS Code	No. of Firms	Description
		Semiconductor Machinery Manufacturing
		Computer Storage Device Manufacturing
3254	12	Petrochemical Manufacturing
3332	6	Semiconductor and Other Electronic Component Manufacturing
		Research and Development in the Physical, Engineering, and Life Sciences
3345	5	Fluid Power Pump and Motor Manufacturing
		Pharmaceutical and Medicine Manufacturing
3344	4	Primary Smelting and Refining of Nonferrous Metal (except Copper and Aluminum)
		Instruments and Related Products Manufacturing for Measuring, Displaying, and Controlling Industrial Process Variables
3251	3	Clay and Ceramic and Refractory Minerals Mining
2122	1	All other Metal Ore Mining
3339	1	Semiconductor and Related Device Manufacturing
5112	1	Medicinal and Botanical Manufacturing
5239	1	InVitro Diagnostic Substance Manufacturing
2123	1	Inorganic Dye and Pigment Manufacturing
3341	1	Electromedical and Electrotherapeutic Apparatus Manufacturing
3314	1	Analytical Laboratory Instrument Manufacturing
5417	1	All Other Financial Investment Activities

Source: Hoover's Company Records 2006

3.2 Initial Trends in Nanotechnology Research

Publications and patents are commonly used indicators of research activity in emerging technologies. These indicators are often used to identify individuals, institutions, and regions that are actively pursuing research in a given area of science and technology. Here, I examine these trends in Nanotechnology domain.

Patenting in nanotechnology is experiencing exponential growth. Unlike other high-technology areas, nanotechnology is marked by a high degree of patenting activity by universities and industry. In addition, several basic ideas are being patented and its implications for the progress of technology are unclear (Lemley, 2005). It is also observed to create significant challenges for maintaining the quality of patent examination and grant processes in an emerging field such as nanotechnology (Sampat, 2005). The fastest growth in nanotechnology patenting has occurred in the past five years in areas such as chemical, pharmaceutical, and semiconductor devices (Huang, et. al., 2003). Figure 3.2 provides a glimpse of activity by US firms in nanotechnology publication, patenting, and participation in public R&D subsidy program such as SBIR. There is a constant rate of growth of patenting activity by firms in the US. In comparison, firms' scientific publications have shown growth in the last five years. This indicates increase in collaborative R&D activities between firms and university researchers. There has been a steady increase in the number of SBIR awards over the past decade.

Evolution of Nanotechnology Industry

The growth in the number of firms in the nanotech industry is depicted in figure 3.3. The name of each firm is counted when it appears for the first time in the publication, patenting, SBIR awardees list, and the list firms with venture capital deals in nanotechnology. Data on venture capital deals is available only until the year 2000. It can be observed from the figure 3.3 that the number of producers is constantly raising with time. This is an empirical regularity observed for new product industries in their early stages (Gort, et. al., 1982). Gort, et. al. observe five distinct stages of new product industries across forty-eight product histories. In the first stage, there are a small number of producers (typically less than three). Entry of firms into the product markets increases significantly in the second stage. The net entry is close to zero in the third stage. The fourth stage is characterized by shake-outs and a small number of firms survive in equilibrium. First-movers into the industry accrue advantages and determine the location of industry in subsequent stages. While a significant increase in the number of firms would suggest a take-off stage, the number of firms by product or application is low. For instance, several products such as 'nanotubes' are based on proprietary technologies exclusively licensed to a single firm (typically from university research). This suggests that the nanotech industry is in Stage I of the Gort-Klepper classification.

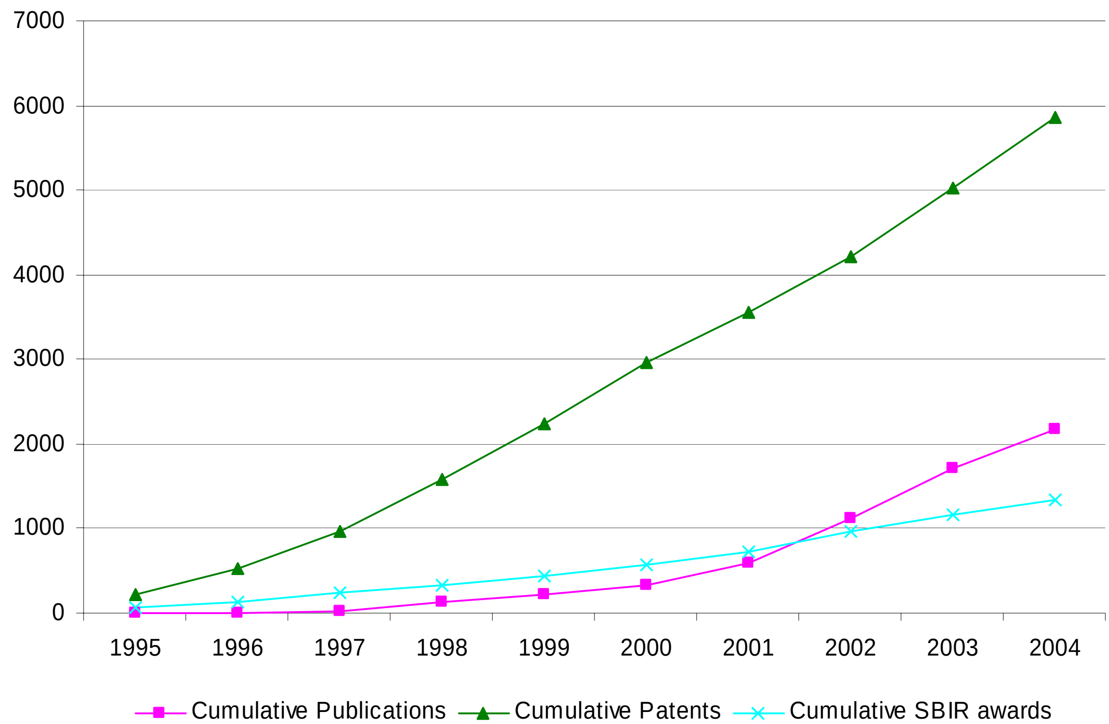

Figure 3.3: Growth in publication, patenting, and research by firms in Nano in the US (1995-2004)
Sources: Science Citation Index, (USPTO, 2006), Nano Definition : (CREA, 2005)

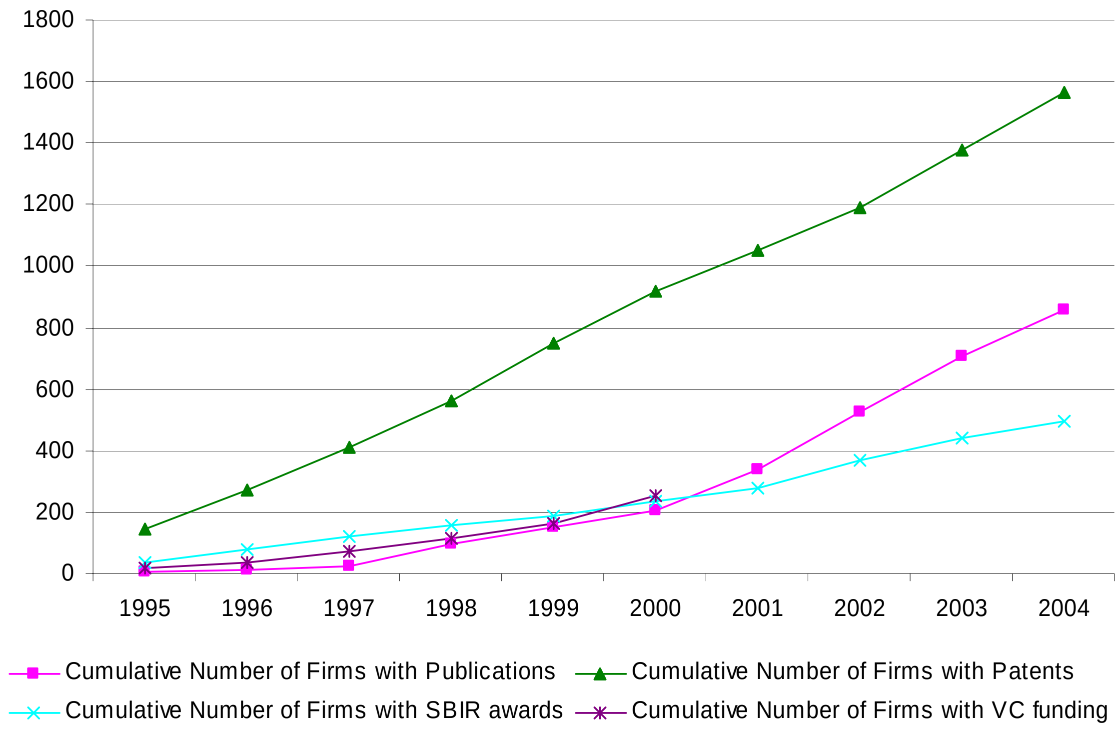

Figure 3.4: Growth in the number of nanotech firms in the US (1995-2004)
Source: Science Citation Index, (USPTO, 2006), Nano Definition: (CREA, 2005)

Visualization of Nanotechnology Industry

I present a series of Geographical Information Systems (GIS) maps that locate the nanotechnology activity geographically in the US. Figure 3.5 depicts the publications by firms in nanotechnology. The publications are selected from Web of Science-Science Citation Index (SCI) using a keyword based definition (see Appendix B) developed as part of CREA Project (CREA, 2005). It can be seen that the publication activity by firms is dominant in two states, California and Massachusetts. Patenting activity by firms is concentrated heavily in similar regions (Figure 3.6). Startups in nanotechnology supported by private venture capital are also concentrated in California and Massachusetts (Figure 3.8).

Public venture capital channeled through SBIR program, however, is heavily concentrated in a few regions in Arizona and Texas (Figure 3.7). Tucson, Arizona has received ninety-two SBIR awards and Austin, Texas received fifty-three in a period 1995 to 2004 as compared to thirty-two awards from Waltham, Massachusetts. This is observed to be due to a small number of firms attracting large number of awards, popularly known as SBIR mills (Lerner, 1999). Hence, controlling for such deviations, the pattern of awardees is not different from the distribution of private venture capital.

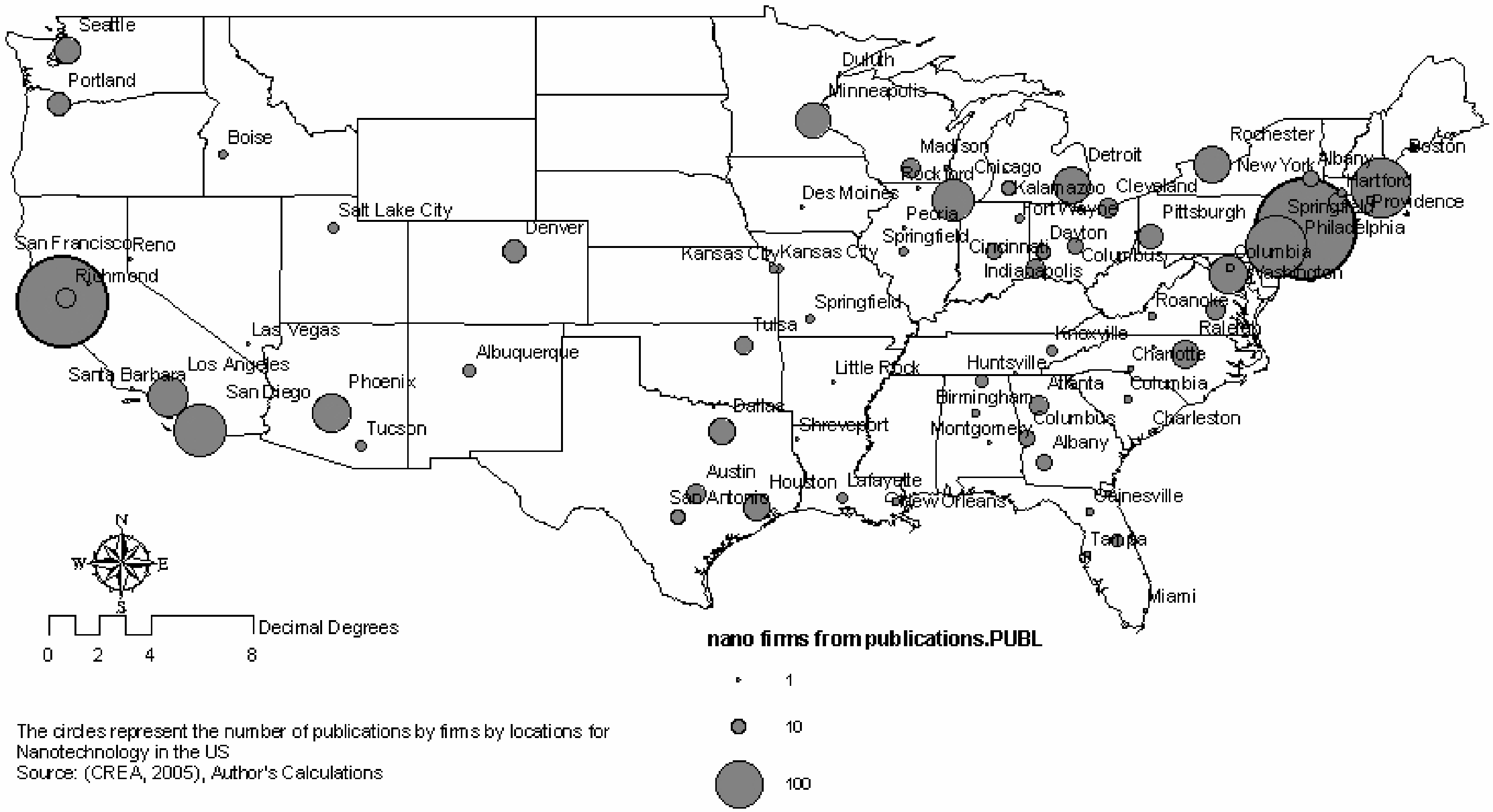

Figure 3.5 Regional Distribution of Publications by Nano Firm affiliated authors
Source: Science Citation Index, (CREA, 2005), Author's Calculations

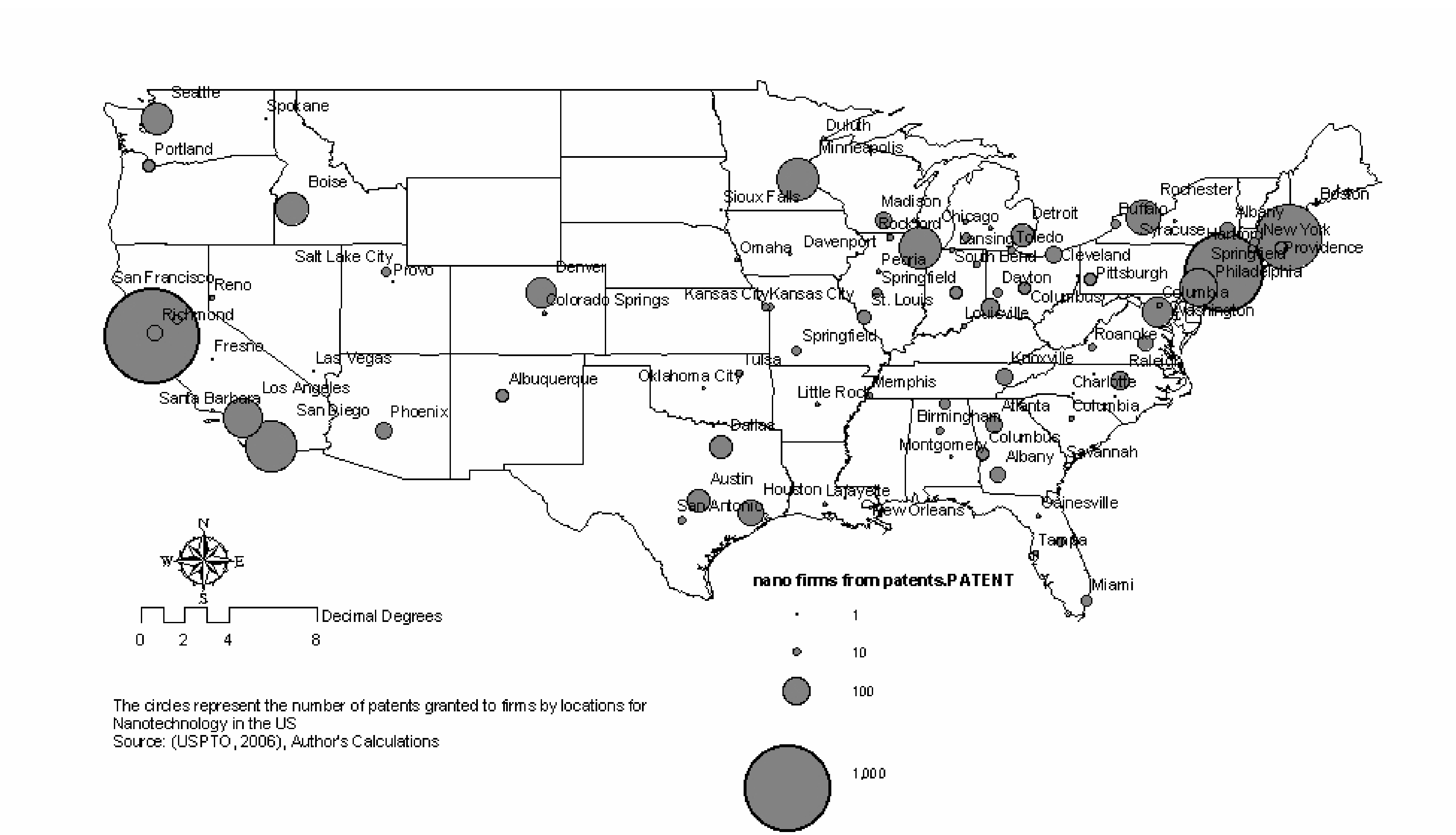

Figure 3.6 Regional Distribution of U.S. Patents by Nano Firm affiliated authors
Source: US Patent and Trademark Office, Author's Calculations

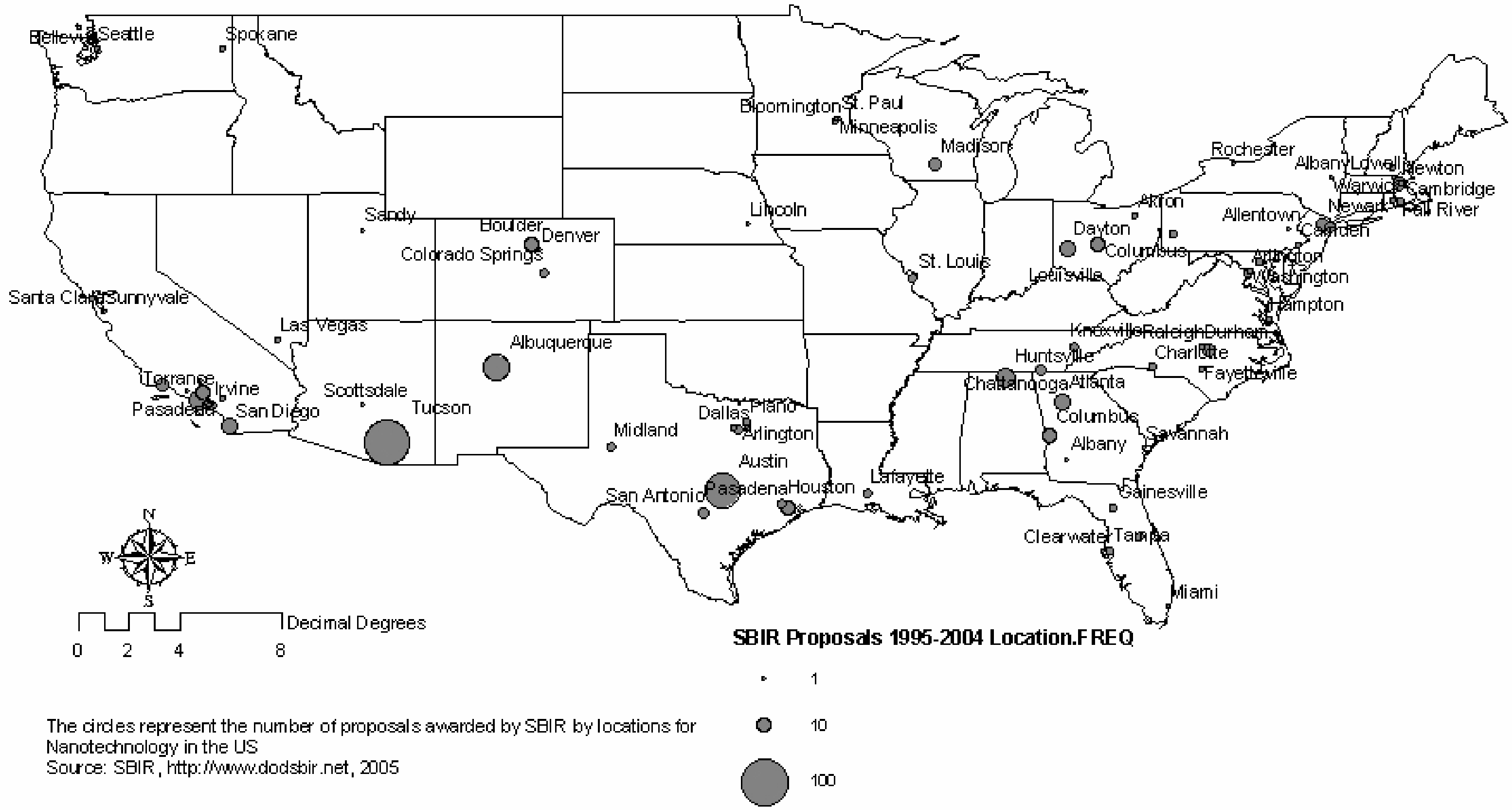

Figure 3.7 Regional Distribution of SBIR awards in nano
Source: SBIR Website (www.dodsbir.net), Author's Calculations

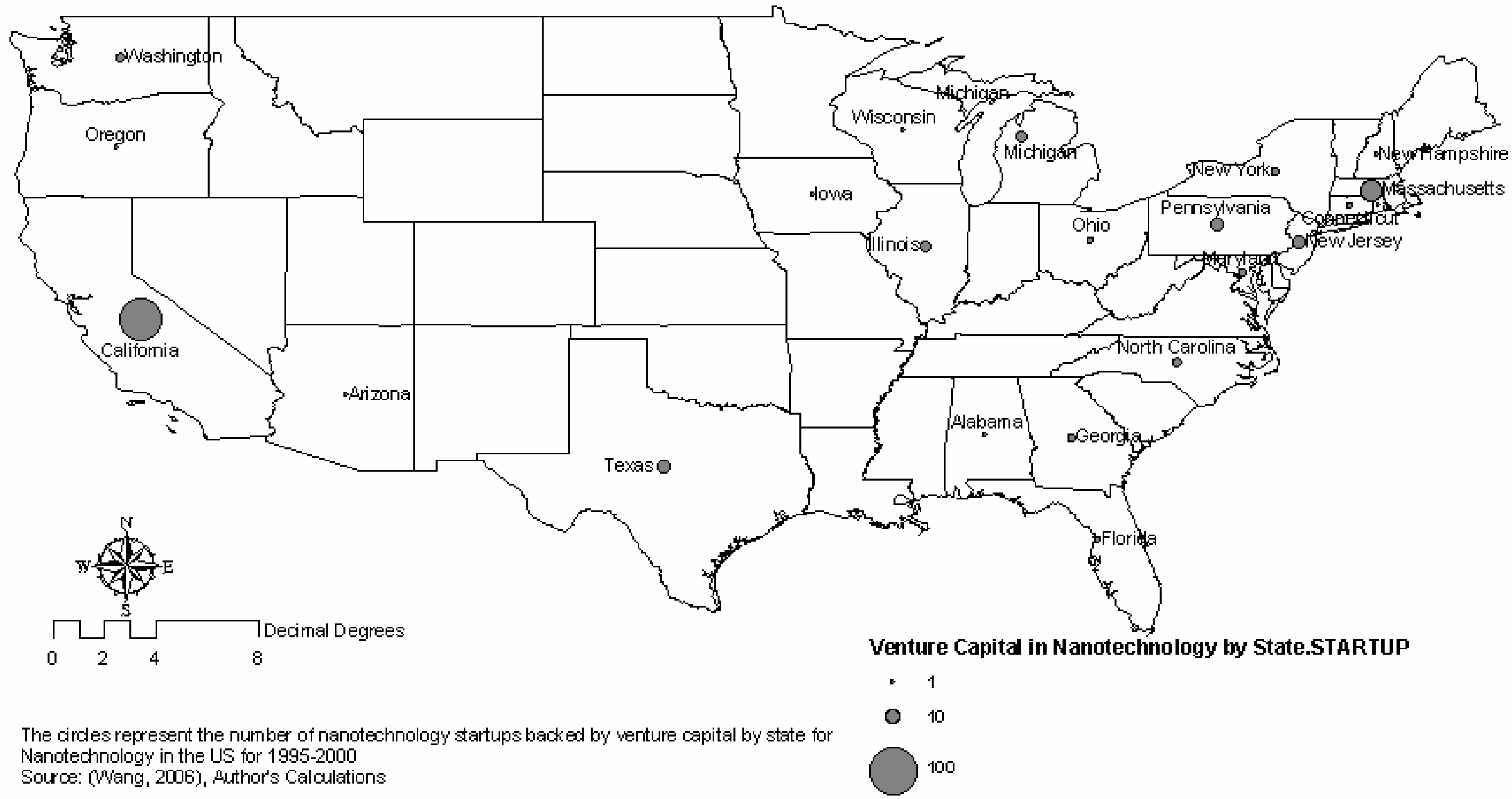

Figure 3.8 Regional Distribution of statups backed by venture capital in nano
Time period: 1996-2000

3.3 Tests of Hypotheses

In this section, I test the hypotheses proposed in section 2.6. Due to limitations of the availability of data only a subset of the proposed hypotheses are amenable for empirical investigation. Specifically, I examine random entry, science driven entry, venture capital driven entry on samples of nanotech firms discussed in section 3.2. While policy driven entry is not examined here, path dependent entry is examined in the context of local universities only.

Random Entry: This hypothesis suggests that the location of entry of nanotechnology firms is random. In other words, the geographical distribution of firms correlates with the population in the US. Regions with a larger population will have more firms and regions with less population will have fewer firms. Table 3.4 tests the hypothesis at the state level. Several measures are included for analysis. First, the numbers of first authors of publications in the nanotechnology domain are listed for each state in column 2. The domain definition is derived from the CREA project and the dataset is constructed for the period 1996-2004. Second, the aggregate numbers publications are listed in column 3. The aggregate numbers of citations to these publications till January 2005 are listed in column 4. Numbers of U.S. patents by state are listed in column 5. Relative shares of these measures with respect to the national averages (also referred to as specialization index) are shown in columns 6-10. For instance, the specialization index (SI) of the number of first authors (x) is calculated for a given state as

$$SI(x) = \frac{number\,of\;\;first\,authors\;per\,million\;population\;per\;state}{number\,of\;\;first\,authors\;per\,million\;population\,in\,US}$$

The relative share of authors varies from 0.09 per state to 3.66 excluding the outlier 9.2. The median value is 0.88. This indicates that several states are close to the national average in terms of their number of nano researchers. The median value increases to 1.39 for the number of nano publications. Seventy percent of the 51 states have SI greater than or equal to 1. However, the quality of nano publications as measured by citations varies greatly across the states. The median value of SI(citations) is 0.62 indicating that while several states are actively publishing in nano, the quality is significantly below the national average for more than half of the states. Distribution of patents by state is further skewed. The median value of SI(nano patents) is 0.44 indicating that several states are below the national average. A similar trend is observable in the location of firm entry. I list the university spinoffs in column 10. While the sample of firms is biased, it represents large sample of firm entry decisions. Seventeen states do not have any entrepreneurial activity as evidenced in the data set. Another third of the states are below the national average. The distribution of research and technology activity in nanotechnology is clearly not random geographically even after controlling for the size of populations in the regions. I test the hypothesis using the specialization index of firms. Let SI(Firms) be θ. Then, H_0: $\theta = 1$ tests whether the states are equally specialized. This implies that the entry of firms is random. On the contrary, H_A: $\theta > 1$ implies concentration of firms across states. Column 10 in Table 3.4 list the sample values of θ. Sample mean for the distribution is 0.94, standard error is 0.19, and 95% confidence interval is [0.56, 1.33]. In addition, $Pr(\theta < 1) = 0.39$, $Pr(|\theta| > |1|) = 0.77$ and $Pr(\theta > 1) = 0.61$. The null hypothesis suggesting equal specialization of states is rejected at the 95% significance level. There is weak support for the concentration hypothesis.

Science driven entry: This hypothesis suggests that since nanotechnology industry is driven by major scientific inventions, it is more likely to locate near universities with significant scientific activity in nanotechnology. In addition, a corollary hypothesis implies that nanotechnology firms are more likely to locate in regions with that host highly cited academic researchers. Table 3.5 shows the intensity of university based entrepreneurial activity regionally. There are more than 200 startup firms founded by university based researchers. By conservative estimates this represents 20-25% of the firms operating in nanotechnology today. This is an indicator of the science driven nature of the firm entry. The number of nano-researchers derived from the publication activity highly correlates (0.89) with the number of patents held by university based researchers. In addition, the number of patents by university based nano-researchers highly correlates (0.94) with the number of nanotech startups. This provides support for the science driven entry hypothesis.

I further investigate whether the distribution of research activity in nanotechnology is significantly different from the research activity in life and physical sciences in the United States in general. I compare the state-level distribution of nano articles from Science Citation Index (SCI) with a random sample of articles for a week from SCI. I compare the state-level distribution of 28460 publications listed in Column 3 of Table 3.4 with 8500 publications in all scientific disciplines added to SCI in the week of April 2, 2006. These publications are affiliated with at least one author based in a US institution. I find the correlation between the two distributions to be 0.9756. This indicates that the distribution of nano research activity builds on the existing regional advantage.

Table 3.4 Relative position of states in the U.S. on various nanotechnology research specialization measures

State	Pop (mil)	# First Authors	# SCI Pubs	Total Citation	# Patents	SI(First Authors)	SI(SCI Pubs)	SI(Citations)	SI(Patent)	SI(Firms)
	Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7	Column 8	Column 9	Column10
United States	296.41	16915	28460	221373	8640	1.00	1.00	1.00	1.00	1.00
Alabama	4.56	200	592	2012	69	0.77	1.35	0.59	0.52	0.32
Alaska	0.66	4	27	3	0	0.11	0.42	0.01	0.00	0.00
Arizona	5.94	274	817	2385	135	0.81	1.43	0.54	0.78	0.97
Arkansas	2.78	74	173	782	17	0.47	0.65	0.38	0.21	1.04
California	36.13	2828	7855	44864	2394	1.37	2.26	1.66	2.27	1.28
Colorado	4.67	291	686	2011	155	1.09	1.53	0.58	1.14	0.93
Connecticut	3.51	249	658	2706	143	1.24	1.95	1.03	1.40	0.00
Delaware	0.84	134	387	1298	92	2.78	4.78	2.06	3.74	1.71
District of Columbia	0.55	289	746	2928	227	9.20	14.11	7.12	14.15	0.00
Florida	17.79	454	1427	4425	69	0.45	0.84	0.33	0.13	0.49
Georgia	9.07	372	1047	4267	79	0.72	1.20	0.63	0.30	0.32
Hawaii	1.28	18	47	127	6	0.25	0.38	0.13	0.16	0.00
Idaho	1.43	46	96	284	152	0.56	0.70	0.27	3.65	0.00
Illinois	12.76	1131	3402	13033	370	1.55	2.78	1.37	0.99	1.02
Indiana	6.27	410	1029	5537	58	1.15	1.71	1.18	0.32	0.00
Iowa	2.97	231	696	2225	40	1.36	2.44	1.00	0.46	0.49
Kansas	2.74	139	298	1300	24	0.89	1.13	0.63	0.30	1.05
Kentucky	4.17	130	402	1083	29	0.55	1.00	0.35	0.24	0.35
Louisiana	4.52	225	650	1637	24	0.87	1.50	0.48	0.18	0.00
Maine	1.32	14	39	110	1	0.19	0.31	0.11	0.03	0.00
Maryland	5.60	823	2421	10774	144	2.58	4.50	2.58	0.88	0.52
Massachusetts	6.40	1335	3703	21608	918	3.66	6.03	4.52	4.92	6.33
Michigan	10.12	586	1672	6016	231	1.01	1.72	0.80	0.78	2.00
Minnesota	5.13	296	799	3349	278	1.01	1.62	0.87	1.86	0.85
Mississippi	2.92	71	193	411	5	0.43	0.69	0.19	0.06	0.00
Missouri	5.80	208	529	1717	83	0.63	0.95	0.40	0.49	0.75
Montana	0.94	31	96	212	2	0.58	1.07	0.30	0.07	0.00

Table 3.4 Relative position of states in the U.S. on various nanotechnology research specialization measures (Contd.)

Nebraska	1.76	100	308	820	20	1.00	1.82	0.62	0.39	0.82
Nevada	2.41	29	82	180	12	0.21	0.35	0.10	0.17	0.00
New Hampshire	1.31	35	80	185	6	0.47	0.64	0.19	0.16	0.00
New Jersey	8.72	487	1280	5056	422	0.98	1.53	0.78	1.66	1.00
New Mexico	1.93	292	905	3754	57	2.65	4.89	2.61	1.01	4.50
New York	19.25	1370	3800	16613	763	1.25	2.06	1.16	1.36	1.05
North Carolina	8.68	558	1514	6957	138	1.13	1.82	1.07	0.55	1.33
North Dakota	0.64	22	50	74	2	0.61	0.82	0.16	0.11	0.00
Ohio	11.46	676	1880	4604	211	1.03	1.71	0.54	0.63	0.63
Oklahoma	3.55	103	260	1171	23	0.51	0.76	0.44	0.22	1.63
Oregon	3.64	119	297	1238	44	0.57	0.85	0.46	0.41	0.40
Pennsylvania	12.43	1044	2739	11137	370	1.47	2.30	1.20	1.02	1.16
Rhode Island	1.08	78	179	499	45	1.27	1.73	0.62	1.43	4.03
South Carolina	4.26	187	547	2195	21	0.77	1.34	0.69	0.17	0.34
South Dakota	0.78	4	12	4	2	0.09	0.16	0.01	0.09	0.00
Tennessee	5.96	353	1238	2821	73	1.04	2.16	0.63	0.42	1.21
Texas	22.86	994	2901	10501	466	0.76	1.32	0.62	0.70	0.89
Utah	2.47	209	470	2964	57	1.48	1.98	1.61	0.79	1.17
Vermont	0.62	38	76	3117	4	1.07	1.27	6.70	0.22	0.00
Virginia	7.57	340	974	422	72	0.79	1.34	0.07	0.33	0.96
Washington	6.29	406	1127	3083	197	1.13	1.87	0.66	1.07	0.23
West Virginia	1.82	20	64	6743	4	0.19	0.37	4.97	0.08	0.00
Wisconsin	5.54	298	775	75	112	0.94	1.46	0.02	0.69	0.78
Wyoming	0.51	11	36	56	4	0.38	0.74	0.15	0.27	5.68

Notes: 1. Population estimates are obtained from U.S. Census Bureau. http://www.census.gov/popest/estimates.php 2. #First authors denotes the aggregate number of first authors of nanotechnology publications. The source of publication data is Science Citation Index for the period 1996-2004. The nanotechnology domain definition is derived from (CREA, 2005). In total, there are 16,915 unique first authors and 28,460 publications in the database. These publications received 221,373 citations as of January, 2005 when the data set was created. 3. Data for U.S. patents is obtained from Community of Science website (patents.cos.com) for the period 1995-2004. Domain definition for patent search is also based on (CREA, 2005). 4. SI in columns 6-10 stands for Specialization Index. SI(x) is a ratio of units of x per million populations in a given state to the units of x per million population in the US. SI(.) measures the relative position of a given state with respect to the U.S. average. 5. All author's calculations related to publications and patents are performed using vantagepoint datamining software.

Venture Capital driven entry: The location of nanotechnology firm entry in the US is determined by the intensity of venture capital available in the region for nanotechnology startup activity. This hypothesis suggests that firm entry is highly correlated with the geographical distribution of venture capital in nanotechnology.

Column 7 in Table 3.5 lists the distribution of the average number of venture capital deals in *any* sector per quarter from 1996 to 2004. Both university startups and venture capital funded nano firms highly correlate with column 7, 0.81 and 0.98 respectively. This hypothesis is difficult to test because we do not have information on those firms that could not enter because they were unsuccessful in finding venture capital support. However, successful regions in nanotechnology are characterized by high concentration of private venture capital. Geographical distribution of public venture capital only moderately correlates (0.64) with the distribution of private venture capital.

Path dependent large-firm driven Entry: The location of nanotechnology firms in the US is determined by the location of large firms diversifying into nanotechnology domain. This hypothesis suggests that the regions with large incumbents in other high technology areas are more likely to become fertile locations for entry of nanotechnology firms. I do not have data on spinoffs from existing firms. In addition, data on spinoffs from federal labs is also not available. However, we can see from column 8 in Table 3.5 that the distribution of public companies with certified market potential are located in states with sizeable research and technology activity by local institutions.

There is recent evidence to suggest that entry by spinoffs leads to co-location as spinoffs tend to locate near parent institutions (Klepper et. al., 2005). Hence, I further

Table 3.5 Relative position of states in the U.S. on various nanotechnology entrepreneurship specialization measures

State	# First Authors	Pat. by Univ Researchers	# Univ Startups	SI(Univ Patents)	SI(Univ Startups)	VC funded Nano firms	VC deals per Q 1995-2004	SBIR Grants in nano	Firms in Market Indices
	Column1	Column2	Column3	Column4	Column5	Column6	Column 7	Column8	Column 9
United States	16915	1149	205	1.00	1.00	166	947.51	1333	37
Alabama	200	19	1	1.40	0.41	1	3.67	17	0
Alaska	4	0	0	0.00	0.00	0	1.00	0	0
Arizona	274	17	4	0.91	1.20	1	8.26	95	0
Arkansas	74	8	2	1.59	2.23	0	1.19	2	0
California	2828	178	32	0.93	0.93	82	349.40	153	10
Colorado	291	10	3	0.51	0.85	0	26.90	54	0
Connecticut	249	23	0	1.36	0.00	2	15.93	41	0
Delaware	134	6	1	0.66	0.62	0	1.41	8	0
District of Columbia	289	0	0	0.00	0.00	0	3.87	2	1
Florida	454	13	6	0.42	1.09	2	20.55	29	0
Georgia	372	37	2	1.46	0.44	3	24.68	19	0
Hawaii	18	0	0	0.00	0.00	0	1.61	1	0
Idaho	46	0	0	0.00	0.00	0	1.28	1	0
Illinois	1131	63	9	0.82	0.66	0	20.78	14	5
Indiana	410	12	0	0.43	0.00	0	2.72	2	0
Iowa	231	20	1	1.27	0.36	1	1.58	0	0
Kansas	139	7	2	0.74	1.19	0	2.60	11	0
Kentucky	130	10	1	1.13	0.63	0	2.94	1	0
Louisiana	225	3	0	0.20	0.00	0	2.53	0	0
Maine	14	0	0	0.00	0.00	0	2.09	1	0
Maryland	823	30	2	0.54	0.20	3	19.08	42	0
Massachusetts	1335	174	28	1.92	1.73	20	101.90	224	5
Michigan	586	33	14	0.83	1.97	5	6.93	32	0
Minnesota	296	17	3	0.85	0.84	0	17.45	17	2
Mississippi	71	0	0	0.00	0.00	0	1.23	1	0
Missouri	208	14	3	0.99	1.19	0	5.78	6	0
Montana	31	0	0	0.00	0.00	0	1.27	2	0

Table 3.5 Relative position of states in the U.S. on various nanotechnology entrepreneurship specialization measures (Contd.)

Nebraska	100	7	1	1.03	0.83	0	1.27	0	0
Nevada	29	0	0	0.00	0.00	0	2.00	3	1
New Hampshire	35	0	0	0.00	0.00	1	6.70	6	0
New Jersey	487	34	6	1.03	1.02	8	23.63	70	2
New Mexico	292	31	6	1.56	1.70	0	1.80	39	0
New York	1370	105	14	1.13	0.84	3	53.93	39	2
North Carolina	558	34	8	0.90	1.18	4	20.78	19	1
North Dakota	22	0	0	0.00	0.00	0	1.00	1	0
Ohio	676	26	5	0.57	0.61	2	11.03	62	0
Oklahoma	103	3	4	0.43	3.20	0	2.06	5	0
Oregon	119	3	1	0.37	0.69	1	8.53	3	1
Pennsylvania	1044	53	10	0.75	0.79	8	29.78	50	3
Rhode Island	78	17	3	3.21	3.17	1	2.26	3	0
South Carolina	187	18	1	1.42	0.44	0	2.46	1	0
South Dakota	4	0	0	0.00	0.00	0	1.25	1	0
Tennessee	353	8	5	0.33	1.17	0	6.58	15	0
Texas	994	77	14	1.14	1.16	8	51.85	80	1
Utah	209	8	2	0.56	0.79	0	7.62	7	1
Vermont	38	0	0	0.00	0.00	0	1.24	1	0
Virginia	340	19	5	0.82	1.21	0	26.80	131	0
Washington	406	9	1	0.33	0.20	4	30.25	12	2
West Virginia	20	1	0	0.74	0.00	0	1.69	0	0
Wisconsin	298	1	3	0.05	0.83	1	3.45	8	0
Wyoming	11	1	2	1.34	15.00	0	1.00	2	0

Notes: 1. #First authors denotes the aggregate number of first authors of nanotechnology publications. The source of publication data is Science Citation Index for the period 1996-2004. The nanotechnology domain definition is derived from (CREA, 2005). In total, there are 16,915 unique first authors in the database. 2 Column 2 represents the number of patents held by university based researchers that have either licensed the technology or found a company. This number is significantly smaller from 8640 (Column 5 Table 3.4) for three reasons: a) Not all patents are licensed or used to start enterprises b) the nano definition used to select these patents is narrow as in (Franks, 1987) c) these are only university affiliated patents. Corresponding number in CREA definition based data set is 1999. 3. SI in columns 4 and 5 stands for Specialization Index. 5. Data on venture capital backed firms is obtained from venture economics for the period 1996-2000. 6. Column 7 lists average number of venture capital deals in the US by state per quarter fro 1995-2004. 7. SBIR Grant proposals are obtained from http://tech-net.sba.gov/tech-net/dsp_search.cfm for the period 1995-2004. 8. Nano related firms listed in various market indices are shown in column 8.

investigate the location of spinoffs with respect to the institution where the nano research was performed. I separately code the current location of the nanotech spinoff firm and the reported history or research and commercialization process. This identifies parent institutions at which the original research was conducted and commercialized. I present the analysis in table 3.6. States with more than one firm lost or gained are depicted in Table 3.6. While thirty-two companies report that their nanotech firm is spun off from research performed at a parent institution in the California state, 29 companies are actually currently located in the same state. The difference at the state level is very small (typically 1) across states for all the states that not listed in Table 3.6. In addition, the difference is zero for 17 states. More broadly, it can be seen that states retain spinoffs from local institutions.

Table 3.6 Location of spinoff firm with respect to parent institution (university) by state

State name	Firm Location	University Location
California	32	29
Massachusetts	28	31
Tennessee	5	7
Oklahoma	4	2
Minnesota	3	1
Maryland	2	4

3.4 Regression Model

I further examine the hypotheses using a regression model. Darby et. al. (2003) develop model specification for entry of nanotechnology firms regionally. They consider 172 regions across the country as specified by Bureau of Economic Analysis. The independent variables included in their study are academic articles in nanotechnology with large number of citations, university level research funding, ranking of the doctoral program in the region, venture capital, employment, and average wage in the region. I use a similar list of dependent variables. Table 3.7 lists the definitions of all the independent variables considered in the study. It also lists the definitions of variables used in the Darby-Zucker study when available. The regional unit of analysis in the present study is a state in the US. The dependent variable used in the Darby-Zucker study is based on the year of authorship of nanotechnology articles by researchers affiliated with a firm in Science Citation Index. In the present study, I use an actual count of the entry of nano firms per state.

I use independent variables that are similar in spirit to those used in Zucker-Darby study. Specialization index of *Nano Citations* measures the share of citations to academic nano articles per million population in a given state to the national average. I expect that the higher the quality of the research in the region, the greater the number of firms entering in the state. I consider three measures of science and engineering capacities of a given state. First, *Academic R&D* per $1000 of Gross State Product (GSP) is considered as an indicator of research orientation of the state. Second, *Academic Productivity* measures the academic article output per $1mill academic R&D in a given state. Third, I use *Advanced S&E Degrees* as share of S&E Degrees Conferred as an indicator of a given state's capacity to supply highly skilled technical workforce. This is similar to the ranking of regions based on the reputation of doctoral programs in the region. These indicators of academic research capacity are expected to positively impact the entry of nano firms, that is, the higher the share of academic R&D, productivity, and reputation, the higher the entry of nano firms in a given state. I further consider whether the technological orientation of the state determines the rate of entry. Specifically, I expect that *Patents* awarded per 1,000 Individuals in S&E occupations in a given state positively impact the entry of firms. I consider two measures of venture capital availability. I expect that the higher the availability of average *SBIR* program award dollars per $1 million of Gross State Product the higher the size of entry. Similarly, private *Venture Captial* disbursed per $1,000 of Gross State Product is expected to have positive impact on the rate of entry. Finally, I consider three measures of employment at the state-level. These measures of employment are oriented towards high-technology sectors. First, I measure employment in high-technology establishments as share of total employment. Second, the share of engineers in the workforce is considered. Third, the share of life and physical scientists in the workforce is measured. These high-tech employment indicators are expected to have a positive impact on the number of firms entering nanotechnology in the state. An important difference to note is that the dataset in the current study is cross-sectional as opposed to the panel data in the Darby-Zucker study. Their model controls for state specific and technology specific fixed effects using panel data. I use a combined list of 342 firms (university spinoffs and venture capital funded firms without duplicates) for the present analysis. Table 3.8 provides a summary of the descriptive statistics of the several variables considered in the regression model.

Table 3.7 Definitions of the variables

Variable	Definition in the current study	Variable in the Darby-Zucker model	Definition in the Darby-Zucker study
Firm Entry	Number of Firms in Nano per state	*Entry*	Year of authorship of SCI article
SI(Nano Citations)	Ratio of Citations to Academic Nano Articles per 1 Million population in the state to the same at the national level	*Article-high-impact* *Articles-top-112*	Count of articles with no firm authors in the ISI High-Impact database
Academic R&D	Academic R&D per $1,000 of Gross State Product (Dollars)	*Research Funding*	Federal funding in millions of 1996 dollars going to top 100 universities as reported by the National Science Foundation
Academic Productivity	Academic Article Output per $1mill Academic R&D	*NONE*	NONE
Advanced S&E Degrees	Advanced S&E Degrees as Share of S&E Degrees Conferred (%)	*Doctoral Programs in top 10*	Count of S&E programs ranked among the top 10 in the U.S. in the 1993 National Research Council study
Patents	Patents Awarded per 1,000 Individuals in S&E Occupations	*NONE*	NONE
SBIR Award	Average SBIR Program Award Dollars per $1 Million of Gross State Product	*NONE*	NONE
Venture Capital Funding	Venture Captial Disbursed per $1,000 of Gross State Product	*Venture Capital Funding* *Venture Capital Deals*	Venture capital funding/deals reported in the Venture Economics
S&E Employment1	Employment in High-Technology Establishments as Share of Total Employment(%)	*Employment*	Jobs per region in millions
S&E Employment2	Engineers as share of workforce (%)	*NONE*	NONE
S&E Employment3	Life and Physical Scientists as Share of Workforce (%)	*NONE*	NONE

Table 3.8 Descriptive Statistics of the variables

Variable	Obs	Mean	Std. Dev.	Min	Max
Firm Entry	51.00	6.71	15.92	0.00	106.00
SI(Nano Citations)	51.00	1.14	1.34	0.09	9.20
Academic R&D	51.00	3.72	1.18	1.72	6.68
Academic Productivity	51.00	3.80	0.79	1.39	5.84
Advanced S&E Degrees	51.00	21.76	6.06	7.90	42.30
Patents	51.00	17.49	12.39	0.90	83.50
SBIR Award	51.00	132.71	131.15	21.00	721.00
Venture Capital Availability	51.00	0.95	1.53	0.00	8.70
S&E Employment1	49.00	7.60	2.17	2.56	11.73
S&E Employment2	51.00	0.93	0.42	0.45	3.09
S&E Employment3	51.00	0.39	0.26	0.14	1.88

I find that the correlation between SBIR Award and Venture Capital Funding is 0.77. I use venture capital funding as an independent variable as it correlates better with the dependent variable. Similarly, the correlation between the share of life and physical scientists with the share of engineering workforce at the state-level is high (0.7). Also, these measures correlate with Advanced S&E Degrees variable. Hence, I exclude indicators of employment and SBIR awards that are correlated with other independent variables.

Darby et. al., (2003) use Poisson regression which is often used to analyze non-negative count data type dependent variable. I follow a similar strategy. I regress the number of nanotechnology firms in a state on several independent variables described earlier. Table 3.9 lists seven alternative models. In models (1), I regress the specialization index of nanotechnology citations on the number of nano firms per state. I find a significant positive relationship between the two variables. 1% increase in the quality of nanotechnology research relative to the national average improves the number of nanotechnology firms by 13%. In model (2), I find that the academic R&D productivity also has a significant positive impact on the entry. This indicates that the regions with existing S&E capacities promote regional entry of nano firms. It can be observed that the relative impact of quality of nano research has reduced from 13% to 6%. In model (3), I use private venture capital availability in the region. Venture capital availability has a significant positive impact on the entry of nano firms. 1% increase in the relative share of venture capital in a state's GSP, results in 54% increase in the number of firm entry. It can also be observed that the impact of citations has become negative. In models (4) and (5), I include Advanced S&E Degrees and Patents variables. I find that the two variables have significant positive impact on the entry.

Table 3.9 Results of Poisson regression for Nanotechnology Firm Entry by state

	I	II	III	IV	V
SI(Nano Citations)	0.131*	0.065**	-0.581*	-0.799*	-0.742*
	(4.84)	(1.99)	(4.12)	(5.32)	(4.96)
Academic R&D Productivity		0.377*	0.090	0.135	0.145
		(4.92)	(0.78)	(1.20)	(1.28)
Venture Capital Availability			0.540*	0.546*	0.500*
			(15.05)	(14.74)	(13.14)
Advanced S&E Degrees				0.062*	0.075*
				(4.57)	(5.19)
Patents					0.016*
					(3.80)
Constant	1.734*	0.336	1.218*	-0.129	-0.758
	(25.68)	(1.12)	(3.37)	(0.27)	(1.46)
Observations	51	51	51	51	51
Pseudo-R^2	0.01	0.04	0.46	0.48	0.49

Absolute value of z statistics in parentheses
+ significant at 10%; ** significant at 5%; * significant at 1%

As hypothesized, we find that regional venture capital and regional indicators of S&E capacities such as the share of advanced S&E degrees have positive impact. However, we find that citations have a negative impact on entry. This is counter intuitive as we expect that an increase in the quality of research increases the regional entry of firms. Such a trend is observed in relation to the location of spinoffs from academic research discussed in section 3.3. I find that more than 95% of the firms locate in the university region. In addition, bias in selection of firms is expected to impact the estimate favorably. Since the sample contains a higher proportion of academic spinoffs, we would expect that the relative impact of citations to be overestimated. In contrast, the observed estimate is negative. The estimate may be biased by the level of analysis. Heterogeneity in citation strengths is more apparent at the MSA level than at the state level and I expect that this may be the reason for the observed negative relationship. In the following chapter, I discuss the implications of these results for science and technology policy and regional economic development.

CHAPTER 4

CONCLUSIONS

This thesis examined the geographic distribution of nanotechnology firm entry. At this early stage in the development of the industry, empirical studies in nanotechnology are constrained by the limited availability of data. This study is no exception. Using a sample of 342 firms in nanotechnology, I find that the distribution of firms geographically is not random. Various measures of research and technology activity in nano indicate the dominance of a few states. For instance, I found that the median values of the specialization indices were less than one for the distributions of publications, patents, venture capital funding across states in nanotechnology. Such a trend is also observable at the MSA level. This indicates that regions remain important in a global world in the context of emerging technologies.

I also find that the number of producers in the nanotechnology industry is constantly rising over time. However, the number of producers in particular markets in nanotechnology is still very small. I find that 20-25% of the young firms in nanotechnology (approximately 205) are spun off from university based research. These firms locate geographically close to the university. I find that less than 0.5% of the firms studied in the sample relocated to a different state after having originated from research activity performed in a given state. Geographical clustering of corporate spinoffs is observed in the context of laser and tire industries in the United States. I find in the present study that a similar phenomenon of locating close to parent institutions extends to spinoffs from academic research.

I find that the specialized public firms in nanotechnology that are listed in nanotechnology market indices are concentrated in a few states such as California, Illinois, and Massachusetts. These small and medium size firms play an important role in the regional innovation. As observed in the U.S. tire industry, the location (Akron) of a few early entrants in an industry can determine the subsequent industry location post 'shakeout' periods. Hence, from a state innovation policy perspective, promotion of innovation in these firms is likely to benefit the region significantly. In addition, I found that these public firms concentrated in a few industry classifications. For instance, several firms were classified as semiconductor machinery manufacturer and pharmaceutical and medicine manufacturers. This finding has two implications. First, we find that the regions with existing capabilities in high-technology areas closely interlinked with developments in nanotechnology have an advantage. Second, regions are likely to specialize in different submarkets in nanotechnology depending on their regional technological history.

Similar to the observed trends in biotechnology, entrepreneurial activity in nanotechnology is driven by a small number of individuals. I found that the number of primary authors of nanotechnology publications differed across the states significantly in aggregate numbers. Forty percent of the authors resided in five states. The distribution of highly cited nano researchers follows a similar trend. As states develop high-technology based economic development policies, the development of a science and engineering workforce becomes an important priority.

States such as Georgia have pursued targeted attraction of entrepreneurial academic researchers. Programs to assist academic researchers in acquiring external sources of R&D and commercialization funding are also widely known. These state level programs attempt to reconfigure the distribution of resources to their favor. It is important to note that the academic entrepreneurial activity is limited to a small number of highly creative individuals. Less is known about the supply of creative individuals and regional factors that promote creativity. These issues are beginning to be explored only recently (Shapira, 2005).

Another issue of interest to policy makers is whether nanotechnology requires sector specific policies. I explored whether the distribution of nano research activity was significantly different from that in life and physical sciences in the US in general. I find that the state-level distribution of nano articles from SCI highly correlate (ρ=0.9756) with a random sample of articles from SCI collected in all scientific disciplines. This indicates that the distribution of nano research activity builds on the existing regional advantage in terms of S&E capabilities.

These issues were further explored in the regression model. Building on the Darby-Zucker model of nano firm entry, I examined the impact of several measures of academic R&D, S&E capabilities, availability of venture capital, and technology orientation of a state. I find that regional academic R&D, availability of venture capital, and state-level propensity to patent have a positive impact on the entry. The negative relationship between citations to nano publications and entry of nano firms is expected to be due to limitations of the level of analysis.

This thesis makes two contributions. First, it contributes to the understanding of the emerging industrial organization of the nanotechnology industry. Specifically, the thesis elaborates on the entry patterns of firms founded by academic entrepreneurial activity. Second, the thesis highlights the strategic nature of the choice location of these entrants.

APPENDIX A

NANOTECH FIRMS IN MARKET INDICES

Table A Nanotechnology Firms on Market Indices

Company Name	Punk Ziegel	ISE-CCM	Merrill Lynch	Global Crown	Lux Research
Elan					x
Accelrys, Inc.	x	x		x	x
Acusphere, Inc.				x	
Affymetrix, Inc.				x	
Altair Nanotechnologies Inc.	x		x	x	x
AMCOL International Corporation			x		
American Pharmaceutical Partners					x
Arrowhead Research Corporation		x		x	x
BioDelivery Sciences International, Inc.				x	
BioSante Pharmaceuticals, Inc.	x		x	x	x
Cabot Corporation		x	x		
Cambridge Display Technologies					x
CombiMatrix Corporation			x		
FEI Company	x	x	x	x	x
Flamel Technol			x	x	x
Harris & Harris Group, Inc.	x	x	x	x	x
Headwaters Incorporated		x	x		x
Immunicon Corporation				x	x
JMAR Technologies, Inc.	x		x	x	
Kopin Corporation	x	x			
Lumera Corporation	x				
MFIC Corporation	x				
MTS Systems Corporation		x	x		
Nanogen, Inc.	x	x	x		
Nanometrics Incorporated		x			
Nanophase Technologies Corporation		x	x	x	x
Nano-Proprietary, Inc.	x				
Nanosphere, Inc.	x				
Novavax, Inc.			x	x	
NVE Corporation	x		x	x	x
Orthovita, Inc.				x	
Pharmacopeia			x		
SkyePharma Inc.	x		x	x	
Symyx Technologies, Inc.	x	x	x		x
Tegal Corporation			x		
Ultratech, Inc.	x	x	x		
Universal Display Corporation		x			
Veeco Instruments Inc.	x	x	x	x	x
Westaim			x	x	x

Table A Nanotechnology Firms on Market Indices (Contd.)

Air Products & Chemicals (APD)	x
BASF (BF)	x
E.I. Du Pont de Nemours & Company (DD)	x
General Electric (GE)	x
Hewlett-Packard (HPQ)	x
Intel (INTC)	x
International Business Machines (IBM)	x
3M (MMM)	x
Toyota (TM)	x

APPENDIX B

CREA DEFINITION OF NANOTECHNOLOGY

Nanotechnology has been defined based on the search terms below. This definition is comprehensive in that it goes beyond the term typically used in nano-related research – nano*. This definition was used in assembling information on publications and patents.

Table B Definition of Nanotechnology

#	Search Filter
1	nano* NOT (nanomet* OR nano2 OR nano3 OR nano4 OR nano5 OR nanosecon* OR (nano secon*))
2	(nanomet* scale*) OR nanometerscale* OR (nanometer length) OR (nano meter length) or nanot* OR nanou* OR nanov* OR nanow* OR nanox* OR nanoy* OR nanoz*
3	nanoa* OR nanob* OR nanoc* OR nanod* OR nanoe* OR nanof* OR nanog* OR nanoh* OR nanoi OR nanoj* OR nanok* OR nanol* OR nanon* OR nanoo* OR nanop* OR nanoq* OR nanor*
4	(atom* force microscop*) or (tunnel* microscop*) or (scanning probe microscop*) or (scanning force microscop*) or (semiconductor quantum dot)
5	(silicon quantum dot) or (quantum dot array) or (coulomb blockade) or (self-organized growth) or (drug carriers) or (positional assembly) or (modified virus) or (molecular templates) or (supramolecular chemistry)
6	(drug delivery OR drug targeting OR gene therapy OR gene delivery) AND (polymer OR particles OR encapsulation OR conjugate)
7	immobilized AND (DNA OR template OR primer OR oligonucleotide OR polynucleotide)
8	polymer AND (protein OR antibody OR enzyme OR DNA OR RNA OR polynucleotide OR virus)
9	(surface modification) AND ((self assembling) OR (molecular layers) OR multilayer OR (layer-by-layer))
10	(self assembling) AND (biocompatibility OR bloodcompatibility OR (blood compatibility) OR cellseeding OR (cell seeding) OR (cell therapy) OR (tissue repair) OR (extracellular matrix) OR (tissue engineering))
11	(self assembling) AND (biosensors OR immunosensor OR biochip OR nanoparticles OR (cell adhesion))
12	Site-specific AND ((gene therapy) OR (drug delivery) OR (gene delivery))
13	encapsulation AND virus
14	(Patterns OR patterning) AND ((organized assemblies) OR biocompatibility OR bloodcompatibility OR (blood compatibility) OR cellseeding OR (cell seeding) OR (cell therapy) OR (tissue repair))
15	(Patterns or patterning) AND ((extra-cellular matrix) OR (tissue engineering) OR biosensors OR immunosensor OR biochip OR (cell adhesion))

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