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Emergence of Nanodistricts in the United States

Path Dependency or New Opportunities?

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Multiple economic development theories suggest that research and innovation in emerging technologies will cluster in certain locations rather than being equally distributed among all regions. If this is the case, this distributional pattern has implications for where future economic opportunities and future risks will be concentrated. In this article, the authors probe nanotechnology research and commercialization at a regional level. The study examines the top 30 U.S. "nanodistricts," or metropolitan areas that lead in nanotechnology research activity, during the 1990 to 2006 time frame. The authors explore the factors underlying the emergence of these 30 metropolitan areas through exploratory cluster analysis. The results indicate that although most of the leading nanodistricts are similar to top cities in previous rounds of emerging technologies, new geographic concentrations of nanotechnology research have surfaced as a result of having made concentrated investments in nanotechnology R&D into a single institution.

Keywords: *nanotechnology; regional clusters*

Nanotechnology, which involves manipulating molecular-sized materials to create new products and process with novel features because of nanoscale properties, is widely anticipated as one of the next drivers of technology-based business and economic growth around the world (President's Council of Advisors on Science and Technology, 2005). Yet even as the field of nanotechnology experiences rapid growth, many questions remain not only about *how* nanotechnology will and should develop but also about *where* it is likely to develop.

Current research suggests that nanotechnology may be deployed as a general-purpose technology that is broadly applicable across the economy with pervasive effects (as discussed by Youtie, Iacopetta, & Graham, 2007). But does being a potential general purpose technology mean that nanotechnology research and innovation activities will emerge in a diverse spread of locations as nanotechnology is developed and applied by a range of institutions and by multiple companies in existing and new industries? Or will nanotechnology research and innovation be focused in a small number of clusters where demonstrated capabilities and expertise for high-technology development are already present? Zucker and Darby (2005) hint that the latter is likely to be the case: They theorize that nanotechnology will follow biotechnology as a science-driven sector and find that, in the United States, there is significant (although not perfect) overlap in the concentration of established biotechnology centers and emerging nanotechnology locations. In contrast, other researchers suggest that nanotechnology will be commercialized not so much via start-up enterprises sited around leading scientific institutions but through the application of nanoscale techniques to

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existing technologies (e.g., microelectronics) by large incumbent firms (Mangematin, 2006). If this is the case, then the regional distribution of nanotechnology activities is likely to be broader, mirroring the existing locations of technology-oriented enterprises across a range of sectors.

Further possible combinations as to the geographical distribution of nanotechnology research and commercialization arise as policy makers themselves seek to influence the development and location of nanotechnology. Global investment in nanotechnology research and development (R&D) is in excess of $4.6 billion annually, with major governmental nanotechnology research initiatives under way not only in the United States but also in the European Union, Japan, China, and Russia (Lux Research, 2006). The U.S. federal government is among the world's leading investors in nanotechnology R&D; the multiagency National Nanotechnology Initiative, with a current annual budget of $1.5 billion, has established more than 80 national nanotechnology centers and networks around the country (National Science & Technology Council, 2007). Moreover, policy makers in at least 30 U.S. states, including those in locations that at the moment are not among the nation's leading high-technology agglomerations, have also sponsored additional research and innovation support programs to capture or grow emerging nanotechnology activities in their regions (Geiger & Hallacher, 2005; Shapira & Wang, 2007). How will these substantial federal and state investments in nanotechnology research influence locations for subsequent nanotechnology commercialization?

More than 20 years have elapsed since the development of the scanning tunneling and atomic force microscopy instruments that first allowed nanoscale empirical investigation. Although the nanotechnology sector is still in its early stages, several hundred products that embody nanotechnology are currently on the market, comprising mostly incremental improvements to existing products (e.g., clothing, sports equipment, paints, and cleaning materials). It may take another decade or more before fundamentally new nanotechnology innovations are commercially introduced. Nonetheless, particularly with the greatly increased focus on nanotechnology since the early 1990s, institutional and corporate locational patterns for nanotechnology are being laid down through the cumulative acquisition of nanotechnology research and innovation capabilities. In this article, we identify the top 30 leading metropolitan locations for nanotechnology research in the United States. Following Mangematin, Rip, Delemarle, and Robinson (2005), we denote these regional clusters of institutes and firms where nanotechnology is emerging as "nanodistricts." Drawing on an exploratory cluster analysis of these 30 U.S. nanodistricts, our study shows that there is a mix of convergence toward already-established high-technology clusters and divergence toward new locations not traditionally associated with high-technology prominence. We show that, although established locations have a diversity of research sources, some of the emerging new locations for nanotechnology are monocentrically led by a single institution, usually either a government laboratory or a university. This reliance on a dominant institution may propel a set of previously less technologically familiar regions into prominence from a nanotechnology research standpoint, but the ability of this research to result in commercial spillovers remains an open question.

Emerging Technologies and Regional Development

There is a long history of analysis on the role of regions in the development of emergent technologies in the context of both theory and policy. Much of this work is empirically focused research seeking to measure aspects of technological development at the regional level. For example, Jaffe, Trajtenberg, and Henderson (1993) find that knowledge spillovers as measured by patent citations are likely to reference patents not just within the national innovation system but also within the home state and metropolitan area of the inventor. Audretsch and Feldman (1996) report that R&D-intensive industries, skilled workers, and university research cluster in particular states even after controlling for the level of production concentration. Other research indicates that knowledge spillovers, tacit exchanges of knowledge, scientific and technical capabilities in the local workforce market, and complementary and supporting industries join with one another to give rise to certain regions being geographic centers for the development of high-technology industries (Aharonson, Baum, & Feldman, 2004; Krugman, 1991; Rosenfeld, 1992). Although extraregional relationships resulting from factors such as telecommunications networks and global knowledge bases certainly influence the processes through which technological advancement and innovation occur (Boschma, 2005), influences within the region still maintain a prominent position in understanding the emergence of new technological domains such as nanotechnology.

Yet although we can anticipate that nanotechnology development will cluster geographically, a fundamental issue is whether nanotechnology is or will be similar to prior high-technology sectors in the way it grows and locates. One perspective is that nanotechnology may be highly regionally path dependent according to the history and current clustering of present research centers, high-tech industries, and complementary assets. For example, Zucker, Darby, Liu, and Ma (2007) find that nanotechnology article production in geographic regions is positively related to the size of prior knowledge stock in *non*-nanotechnology research areas as measured by the discounted cumulative counts of non-nanotechnology articles authored by scholars working in certain U.S. Bureau of Economic Analysis regions. The authors conclude that prominence of regions such as Northern California's Silicon Valley in prior technological areas gives these geographic regions a cumulative advantage in the production of nanotechnology research.

However, the fields of expertise involved in nanotechnology are many, including physics, chemistry, materials science, life sciences, and electrical engineering. Similarly, the variety of uses is extensive, including coatings, cosmetics, electronics, energy, environmental control, medicine, new materials, packaging, and textiles, with further applications ranging from the everyday to the highly sophisticated envisaged in the future. The generality of nanotechnology suggests that a broad set of additional factors may influence its development from a regional perspective. For example, Mangematin (2006) proposes that capital investment in large, existing public and private research facilities might be important in attracting nanotechnology-related firms, much as was the case with microelectronics. Mangematin emphasizes the importance of research facilities with ultraclean rooms and specialized equipment of the type observed in Grenoble, France, where a nanotechnology complex has emerged involving STMicroelectronics, other information technology companies, the Crolles 2 Research and Advanced Manufacturing Facility, and the Minatec Nanotechnology Research Center.

A focus on capital and facilities investment raises the importance of the institutional context. Although not specifically focusing on nanotechnology, Agrawal and Cockburn (2003) highlight the role of large anchor-tenant firms in the concentration of patents in medical imaging, neural networks, and signal processing industries in the same metropolitan area in which these firms are located. In contrast, Shapira, Youtie, and Mohapatra (2003), in their study of regional information and communication technology clusters, suggest that regions with more diverse research sources might have an advantage with respect to the development of technological areas over those characterized by a smaller number of institutional resources. The diversity of institutional resources and their interrelationships is further reflected in the finding of Zucker et al. (2007) about the importance of cross-institutional coauthorships in intraregional nanotechnology article and patenting production.

A contrasting view to that of the facilities-based perspective is Davenport and Daellenbach (2006) who indicate that nanotechnology activity in New Zealand, not a conventional setting for concentration of emergent technologies, has occurred around publication networks encompassing prominent scholars rather than around "bricks and mortar." This perspective recalls research on the roles of networks in emerging research areas such as Rogers and Bozeman's (2001) concept of the knowledge value collective, in which diverse researchers and industry users have common knowledge needs that influence the progress of scientific and technical areas depending on their awareness of the body of knowledge, breadth of skills, and interactions and consciousness of one another (also see Bozeman & Rogers, 2002). Another human capital-related factor argued as influential in the localization of high-technology industries is the presence of researchers (or "star scientists") who not only lead their field but also are active in networking and commercialization. Zucker, Darby, and Brewer (1998) report that start-up biotechnology firms are more apt to locate near universities, where star scientists conduct research. Audretsch and Stephan (1996) further find that the importance of university research in biotechnology firm location depends on whether the university scientist has a central role in the firm, such as having founded it. In nanotechnology, Heinze (2006) has investigated the impact of star scientists, along with investments, public attention cycles, interorganizational networks, and publications and patents.

This brief review of the literature highlights multiple factors that may influence where nanotechnology research and commercialization gravitate. These factors include path-dependent stocks of knowledge, capabilities, finance and other resources, business- or policy-induced capital investments in facilities, institutional strategies and linkages, and talent and human capital availability. Although all factors may plausibly have relevance, a greater impact of one over others in nanotechnology development will have regional implications. If nanotechnology follows a similar trajectory to biotechnology, places in the northeastern United States and California will be most favored (with the exception of the Research Triangle in North Carolina). (See Cortright and Mayer [2002] for an analysis of U.S. biotechnology locations.) An institutional viewpoint that nanotechnology R&D will converge on regions with an accumulation of institutional assets, such as large-scale research facilities and anchor-tenant organizations, may emphasize regions that have large government laboratories or dominant research universities that feature specialized facilities and equipment. If human capital capabilities such as scholarly networks and leading scientists are key, nanotechnology could be divergent, spread not only in the few metropolitan areas that have demonstrated R&D capabilities such as Silicon Valley and Boston but also in other parts of the country that have attracted and developed high levels of local researcher capabilities and linkages. There are many possible questions here, but in sum our research asks, will nanotechnology be path dependent, clustering where prior rounds of technologies, such as biotechnology, have predominated? Or are there opportunities for new geographic concentrations of research, and, if so, what is the potential for commercialization in these new locations?

Data and Methods

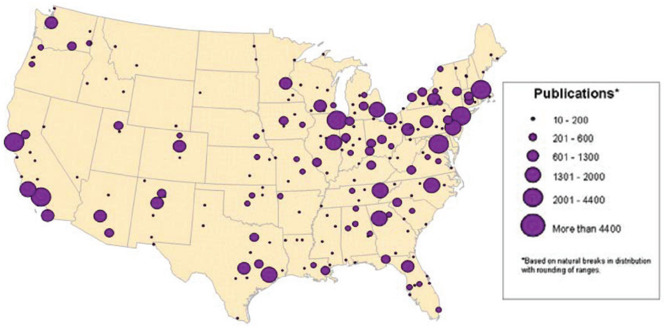
In this study, we examine these arguments and the respective factors they prioritize relative to the clustering of nanotechnology-related research activities in U.S. metropolitan areas. Although we also perform a parallel analysis with patent data, this study uses scientific publication as a starting point, for several reasons. From a substantive standpoint, developmental patterns for emerging technologies such as nanotechnology are often first revealed in research publications rather than patenting (even taking into account exceptions such as prohibitions to publish in intellectual property agreements until the intellectual property has been disclosed). Although most scientific publications are produced by academic and other public research institutions, private corporations also produce their own publications and coauthor with institutional scientists, and these can offer early signals of business interest in a new technological domain. From a methodological standpoint, publications usually have more consistent geographic information about the author than do patents with regard to inventors and assignees.

Our analysis of nanotechnology publications draws on databases built at Georgia Tech with support from the National Science Foundation–sponsored Center for Nanotechnology in Society at Arizona State University. The search approach and method are presented in detail in an article (of which the authors of this article are coauthors) by Porter, Youtie, Shapira, and Schoeneck (2008).[1] In outline, a bibliometric definition of nanotechnology was developed using a two-stage modularized Boolean approach. An expert review process involving 19 nanotechnology scientists and engineers assisted the Georgia Tech team in refining this definition. The resulting search terms were used to develop publication data sets for the 1990 to 2006 (midyear) period. This approach identified more than 400,000 global nanotechnology records in the Web of Science's Science Citation Index (WOS-SCI).

The U.S. nanotechnology publications resulting from this WOS-SCI search were assigned to a location according to the city and state of the institution associated with the author or authors indicated in the publication record. One challenge is that the WOS-SCI records do not always cleanly match the institution and the geographic location beyond that of the first author. Nevertheless, this study seeks to go beyond the first author. In addition, we used external listings of the local city and state affiliations of universities and government laboratories to assign these organizations to our focal regions. However, we were not able to do this matching with complete accuracy for private industry. Private firms may have a local office in a particular city and state separate from their headquarters location, and they also vary with respect to their policies for assigning publications to the headquarters office or the local office. Moreover, there are often a few private sector firms that account for the majority of private sector–generated publications in a metropolitan area and a larger number of firms with only one or two publications. Although we could identify and assign the firms producing the majority of publications by metropolitan areas, we could not cleanly check the geographic affiliations of those companies with just one or two publications. This issue with assigning private industry to a geographic location is a limitation of our study, but it primarily affects firms with one or two publications associated with a metropolitan area.

The counts of publications within individual city and states are aggregated to the U.S. metropolitan area level. Combined statistical areas (CSAs) and metropolitan statistical areas that are not within the boundaries of a CSA as delineated in December 2006 by the Office of Management and Budget (2006) compose our level of analysis (hereafter referred to as metropolitan areas). Geographic assignments of publications are based on the city and state of the author as reported by WOS-SCI and patents are based primarily on the inventor city.[2] There are 212 metropolitan areas (and a few "micropolitan" areas) with 10 or more publications, which are mapped in Figure 1. The size of the circle at the centroid of the largest city in the metropolitan area represents the number of publications as indicated in the map legend. Although there is dispersion in nanotechnology publications across several hundred research locations, at the same time much of the nanotechnology research is

Figure 1
Nanotechnology Publications, U.S. Metropolitan Areas and Other Cities, 1990 to 2006



Source: Based on nanotechnology definition in Porter, Youtie, Shapira, and Schoeneck (2008).
Note: Geography includes metropolitan areas (centroid, largest city), combined statistical area (centroid, largest city), and other cities not in the aforementioned. City must have 10 or more nanotechnology publications in Science Citation Index 1990 to midyear 2006.

disproportionately concentrated in a few metropolitan areas. The top six metropolitan areas—New York, San Francisco–San Jose, Boston, Washington, D.C.–Baltimore, Chicago, and Los Angeles—account for 38% of the publications while composing 24% of the population.[3]

In the analysis reported in the balance of this article, we focus on the top 30 metropolitan areas, which each accounted for at least 1% of U.S. nanotechnology publications in the 1990 to 2006 (midyear) period. Table 1 presents these top 30 nanodistricts, along with their publication counts. It is acknowledged that this breakpoint is based on judgment; we could have raised or lowered the entry threshold, resulting in fewer or more metropolitan areas. We note that the 30 metropolitan areas included in our current analysis accounted for nearly 84% of all U.S. nanotechnology publications in the study period (1990 to 2006) while composing 44% of the U.S. population (in 2000). All but three of the metropolitan areas contributed a higher percentage to total nanopublications than their percentage of the nation's population.

To explore the factors involved in the development of these nanodistricts, we focus on a set of variables that represent the major positions outlined in the development of emergent research clusters (see Table 1). We recognize that some of these factors are influenced by the size of the metropolitan area, such as publication counts, whereas others reflect institutional or human capital factors that are related to quality rather than a direct function of size. The following paragraphs discuss how we operationalize our factor concepts.

The concepts of path dependency and cumulative advantage build on arguments that regions maintain technological leadership through early entry and positional lock-in, the development of scale and capability, and learning and the accumulation of knowledge (Fuchs & Shapira, 2005). We broadly model these concepts by two measures: the total number of nanotechnology publications (to proxy accumulated knowledge and scale) and the percentage of these publications in the early period of 1990 to 1995 (to proxy potential advantages gained from early entry).

Our literature review highlighted debate about the role of large research organizations (anchor tenants) versus a diversity of research producers and sources in the development of technology-oriented regions. In our analysis, we measure regional economic concentration using the Herfindahl Index (*H*),

$$H = \sum\nolimits_{j}^{n}{}_{i}\, s_{ij}^{2},$$

where Sij = share of institution i*'s* publications in metro j. H values of 1.0 indicate that the sources of nanotechnology publications in a nanodistrict are concentrated into a single organization, whereas values close to zero indicate that there are high degrees of diversity in publication sources. The facilities-based perspective on nanotechnology's development is represented by the percentage of publications from government-owned laboratories.

For human capital factors, the "star scientist" concept is captured by the percentage of all publications in a nanodistrict that are highly cited, meaning they have been cited at least 25 times in the period 2001 through mid-2006. We focus on more recent citations to capture work that is currently assessed by peers as of high quality. We acknowledge that citation-based measurement of scientific quality does have limitations because of time lags, self-citations, negative citations, discipline differences, and referee additions (Dosi, Llerena, & Labini, 2005; Glanzel, Thijs, & Schlemmer, 2004). Still, within these limitations, citations of publications are a commonly used measure of research significance and influence.

The relative importance of networking and collaboration by researchers is represented by a sample ratio of authors to articles. We have also included a measure of nanobiotechnology specialization. Specialization in particular industry segments has been central to the study of regional clustering and agglomeration (Malmberg & Maskell, 1997). In addition, as discussed earlier, the star scientist concept arose from the study of the biotechnology industry, and there has been a current of debate that

Table 1
Top 30 U.S. Metropolitan Nanodistricts by Publication Output, 1990 to 2006 (Midyear)

Metropolitan Area	Abbreviation	Nanopublications 1990 to 2006 (Thousands)	Percentage of U.S. Nanopublications 1990 to 2006	Percentage of U.S. Population 2000
1. New York–Newark–Bridgeport, NY–NJ–CT–PA	NY	9.6	9.1	7.6
2. San Jose–San Francisco–Oakland, CA	SF–SJ	8.7	8.2	2.5
3. Boston–Worcester–Manchester, MA–RI–NH	Boston	7.4	7.0	2.6
4. Washington–Baltimore–Northern Virginia, DC–MD–VA–WV	DC–Balt	7.1	6.7	2.7
5. Los Angeles–Long Beach–Riverside, CA	LA	5.4	5.1	5.8
6. Chicago–Naperville–Michigan City, IL–IN–WI	Chicago	4.4	4.2	3.3
7. Philadelphia–Camden–Vineland, PA–NJ–DE–MD	Philadelphia	3.2	3.0	2.2
8. Raleigh–Durham–Cary, NC	ResTri	3.1	2.9	0.5
9. Champaign–Urbana, IL	Champaign	3.0	2.8	0.1
10. Santa Barbara–Santa Maria, CA	Santa Barbara	2.6	2.5	0.1
11. Detroit–Warren–Flint, MI	Detroit	2.4	2.3	1.9
12. Houston–Sugar Land–Baytown, TX	Houston	2.3	2.2	1.7
13. Atlanta–Sandy Springs–Gainesville, GA–AL	Atlanta	2.2	2.0	1.6
14. Knoxville–Sevierville–La Follette, TN	Knoxville	2.2	2.0	0.3
15. State College, PA	State College	1.9	1.8	0.0
16. Cleveland–Akron–Elyria, OH	Cleveland	1.9	1.8	1.0
17. Minneapolis–St. Paul–St. Cloud, MN–WI	Minneapolis	1.9	1.8	1.2
18. Austin–Round Rock, TX	Austin	1.7	1.6	0.4
19. Phoenix–Mesa–Scottsdale, AZ	Phoenix	1.7	1.6	1.2
20. Albuquerque, NM	Albuquerque	1.7	1.6	0.3
21. San Diego–Carlsbad–San Marcos, CA	San Diego	1.6	1.5	1.0
22. Pittsburgh, PA	Pittsburgh	1.6	1.5	0.9
23. Denver–Aurora–Boulder, CO	Denver	1.6	1.5	0.9
24. Ithaca, NY	Ithaca	1.6	1.5	0.0
25. Gainesville, FL	Gainesville	1.4	1.4	0.1
26. Madison, WI	Madison	1.4	1.3	0.2
27. Seattle–Tacoma–Olympia, WA	Seattle	1.3	1.2	1.3
28. Lafayette–West Lafayette, IN	Lafayette	1.2	1.2	0.1
29. Albany–Schenectady–Amsterdam, NY	Albany	1.2	1.1	0.4
30. Dallas–Fort Worth, TX	Dallas	1.1	1.1	2.0
Total		88.6	83.5	43.9

Source: Nanotechnology publications are based on search terms and data sources detailed in Porter, Youtie, Shapira, and Schoeneck (2008), metropolitan area definitions are from Office of Management and Budget (2006), and population estimates are from U.S. Census Bureau (2007).

compares the regional development of biotechnology in the 1980s and 1990s with nanotechnology in the current decade (Zucker & Darby, 2005). In our analysis, we measure the research publication subject matter specializations of each nanodistrict using the Thomson Scientific classifications of journals aggregated up to broad research areas. Nanobiotechnology includes biology and medicine subject areas.[4] It can be argued that biotechnology and nanotechnology have substantial field overlaps. However, our original database development drew on advice from the survey of nanotechnology scientists and engineers to exclude terms outside the scale of nanotechnology, such as *DNA* and *RNA*, unless they appeared with a core nanotechnology keyword, such as *nanoarray* or *self-assembly* (Porter et al., 2008).

These measures were calculated for each of the 30 U.S. nanodistricts with 1,000 or more nanotechnology publications and are summarized in Table 2. They were then used as the basis of a hierarchical cluster analysis of these cities. Hierarchical cluster analysis employs an algorithm that starts with each case (i.e., each nanodistrict) in a separate cluster and combines clusters in stages based on a set of attributes of the cases such that they eventually converge into a single grouping. The measures we used to reflect the major attributes of each nanodistrict were standardized so that they received equal

Table 2
Variables Used in Cluster Analysis: Descriptive Statistics

Concept	Variable	Mean	Median	SD	Min	Max
Path dependency	Total number of nanotechnology publications (pubtot)	2,954	1,929	2,329	1,066	9,612
Path dependency	Proportion of all publications published in the 1990 to 1995 time period (pubs1990-1995)	0.12	0.12	0.03	0.06	0.19
Facilities	Proportion of publications authored by researchers at a government-owned laboratory (govpub)	0.12	0.01	0.22	0.00	0.83
Institution	Herfindahl Index based on number of publications by institutional affiliation of author (herfpub)	0.46	0.40	0.29	0.05	0.98
Human capital	Proportion of all publications that have 25 or more citations (highcite)	0.06	0.05	0.04	0.03	0.24
Networks	Ratio of number of authors to number of articles (authart)	2.04	2.08	0.36	0.60	2.64
Path dependency, specialization	Proportion of publications in the nanobiotechnology area (nanobio)	0.11	0.11	0.05	0.03	0.20

Source: Analysis by authors based on search terms and data sources detailed in Porter, Youtie, Shapira, and Schoeneck (2008).
Note: Descriptive statistics reported for 30 metropolitan areas are listed in Table 1.

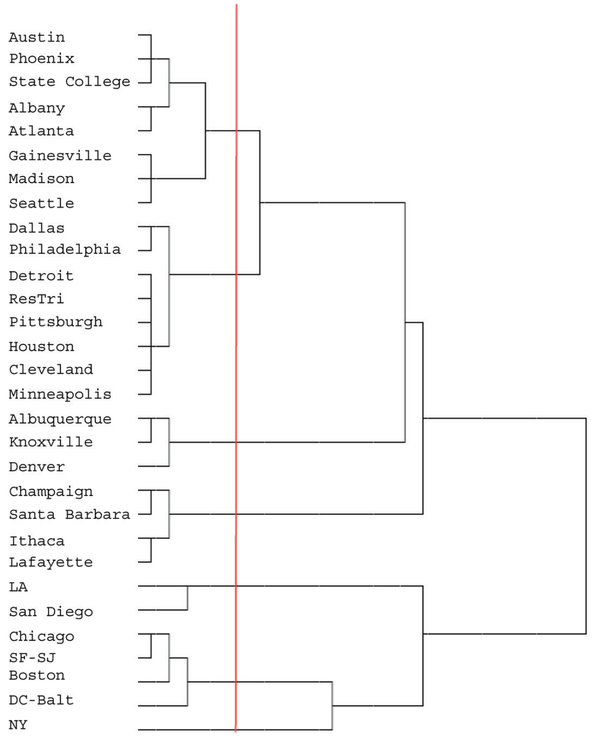
weight in terms of influencing the clustering. Ward's method of using squared Euclidean distances was employed. Because distance algorithms can be subject to case ordering influences, the analysis incorporated several random variables to introduce variations in case ordering, although we did not find our solution was affected by these variations (Aldenderfer & Blashfield, 1984).

Although cluster definitions are determined based on publication characteristics, we then added patent measures so as to be able to describe clusters in terms of both research and innovation attributes. Patents are granted to inventions that are novel, nonobvious, and useful; as such, when measured at the regional level, they can signal capabilities for innovation and the ability to apply and commercialize knowledge. Our patent information is based on nearly 54,000 global nanotechnology-related abstracts of patents awarded in the same time frame (1990 to 2006 midyear) reported from the MicroPatents database. These patents are determined to be in the nanotechnology field based on the use of a definition similar to that used for nanopublications. The U.S. nanotechnology patents resulting from the MicroPatents search have been assigned to the U.S. city and state of the inventor. For the most part, assignments reflect the first inventor, although an effort to profile all authors or inventors involved in nanotechnology patenting is made. Patents are then regionally aggregated in the same manner that we used for publications.

Results

The results of the cluster analysis are illustrated in the dendogram are shown in Figure 2. This dendogram is used to facilitate a sensitivity analysis to explore the optimal number of clusters for examination. The exploratory nature of cluster analysis means that any number of solutions may be generated (up to 30, or 1 for each metropolitan area). After considering multiple options, we judge that a seven-cluster solution is the most useful option for categorizing the set of U.S. nanodistricts. We examined the six-cluster solution but did not choose it because it would group more than half of the nanodistricts together (including Dallas–Fort Worth, Texas; Philadelphia, Pennsylvania; Detroit, Michigan; Research Triangle Park, North Carolina; Pittsburgh, Pennsylvania; Houston, Texas; Cleveland, Ohio; Minneapolis, Minnesota; Austin, Texas; Phoenix, Arizona; State College, Pennsylvania; Albany, New York; Atlanta, Georgia; Gainesville, Florida; Madison, Wisconsin; and Seattle, Washington), thereby yielding too little variation. We also considered an eight-cluster solution, (which separates Gainesville, Madison, and Seattle into an additional eighth cluster), but this option was judged to be less parsimonious than the seven-cluster solution. Membership of the nanodistricts in the seven-cluster solution is listed in Table 3.

Figure 2
Hierarchical Cluster Analysis Dendogram



Note: Continuous vertical line indicates seven-cluster solution described in text.

Table 3
Nanodistrict Cluster Composition

Seven Cluster Designation	Abbreviation	Cluster Membership by Metropolitan Nanodistrict
Middle focused	FOC	Albany Atlanta Austin Gainesville Madison Phoenix Seattle State College
Government	GOV	Albuquerque Denver Knoxville
Techno leaders	TLEAD	Boston Chicago SF–SJ DC–Balt.
University	UNIV	Champaign Ithaca Lafayette Santa Barbara
Middle diverse	DIV	Cleveland Dallas Detroit Houston Minneapolis Philadelphia Pittsburgh ResTri
Southern California Nanobio	SCAL	LA San Diego
New York	NY	NY

To understand the attributes of these clusters, we have reported median values for these clusters on several nanotechnology publication and patenting attributes (see Table 4). These attributes are used in the following paragraphs to characterize the nature of the clusters.

The metropolitan areas of Boston, San Francisco–San Jose (Bay Area), Washington, D.C., and Chicago (denoted as technology leaders or TLEAD in Table 3) represent a forefront cluster in terms of aggregate numbers of publications and have the highest percentage of early period publications (1990 to 1995). They have diversity in institutional research sources with a low Herfindahl Index number. These metropolitan areas also have a relatively higher percentage of publications specializing in nanobiotechnology. They have a large number of patents as well, suggesting localized commercialization capabilities. The New York (NY) metropolitan agglomeration is very much like them but even larger in scale based on number of publications. New York's publication domain also has more articles authored by corporate-affiliated researchers and is more specialized in nanoelectronics, likely a reflection of the influence of IBM and other area organizations. However, there is a lower level of networking with other authors based on the ratio of authors per article. New York appears as a top-end outlier in this analysis, and it might be presumed that this is so because it serves as a headquarters location of major corporations. However, we find that the large New York metropolitan area is diverse and includes a varied set of corporate and academic institutions prominent in the nanotechnology area, including not only IBM and AT&T but also Columbia, Rutgers, and Princeton.

The cluster encompassing Los Angeles and San Diego (SCAL) has the next highest number of aggregate publications. This cluster is the most concentrated in nanobiotechnology and has a specialization percentage in this broad field that is slightly higher than the leading group. The cluster also rates particularly high in star scientists as measured by the percentage of highly cited publications and networking as measured by the authors per article ratio.

Table 4
Nanotechnology Publication and Patenting Characteristics by Cluster

Characteristics	New York	Techno Leaders	Southern California Nanobio	Middle Diverse	University	Government	Middle Focused
	NY	TLEAD	SCAL	DIV	UNIV	GOV	FOC
pubtot	**9,612**	**7,257**	3,525	2,129	2,107	1,683	1,590
pubpmil	449	974	454	546	**10,438**	2,296	1,208
corppub (%)	**36.6**	10.5	11.8	13.4	4.1	8.2	7.9
unipub (%)	58.3	72.9	81.1	86.8	**98.7**	43.4	**93.5**
govpub (%)	7.8	26.5	7.1	1.3	0.0	**64.5**	0.2
nanobio (%)	13.8	**14.0**	**16.6**	13.7	8.2	3.9	8.6
herfpub	0.045	0.170	0.194	0.335	0.909	0.417	0.764
highcite (%)	5.0	6.1	**21.2**	4.8	4.3	3.1	4.3
authart	0.60	2.12	**2.36**	2.09	1.76	**2.20**	2.08
pubs1990-1995 (%)	**18.0**	11.9	10.9	11.4	19.2	10.1	10.5
pubs2001-2006 (%)	54.6	60.4	59.8	62.9	53.3	60.6	**64.8**
totpat	**3,012**	1,603	853	546	98	237	295

Note: Median values are reported. See Table 2 for reference to data sources and variable descriptions. Additional variables shown here include pubpmil (total number of nanotechnology publications per million population), corppub (percentage of publications with an author affiliated with a corporation), unipub (percentage of publications with an author affiliated with a university), pubs2001-2006 (percentage of articles published in the 2001 to 2006 [midyear] period), totpat (total number of nanotechnology patents 1990 to 2006 [midyear]). The values that are highest across the row are shown in bold.

Universities play a prominent role in nanotechnology research, but they are especially dominant in a set of four metropolitan areas: Champaign–Urbana (University of Illinois at Urbana–Champaign), Ithaca, New York (Cornell), Lafayette–West Lafayette, Indiana (Purdue University), and Santa Barbara (University of California, Santa Barbara). Research in the cities of this cluster (UNIV) is highly dominated by a single research university based on the percentage of research undertaken by universities. In addition, this category has the highest Herfindahl Index value of any of the clusters, also indicative of the domination of research by a single entity. This group had a notable percentage of early-era publications, suggesting that researchers at these institutions were among the first to conduct nanotechnology research. At the same time, this cluster of cities has the lowest number of patents.

In a similar vein, we also see a distinct set of metropolitan areas that are dominated by one or two government-owned facilities: Knoxville–Oak Ridge (Oak Ridge National Laboratory), Albuquerque (Sandia National Laboratory, Los Alamos National Laboratory), and Denver (National Renewable Energy Laboratory, National Institute of Standards and Technology). Nearly two-thirds of all publications in this cluster (GOV) are authored by individuals at these government-owned facilities. In addition, these nanodistricts seem to pursue networked relationships, as they have a very high author-to-article ratio and their Herfindahl value is lower than that of the university-dominated cluster. One reason for this lower value is these government-led nanodistricts often include at least one local university, although the aggregate publication count associated with this university is usually not as high as that of the laboratory. We also note that although these nanodistricts are dominated by government-affiliated publications, most of the patents are owned by companies, in part because the contractors operating these facilities (which have title to intellectual property developed therein) often are private companies. There might be some question as to why the D.C.–Baltimore metropolitan area does not fall into this group of government-dominated nanodistricts. The D.C.–Baltimore region does have a high share of government-authored publications (nearly 65%). However, this region's large publication base and low Herfindahl Index (less than .09) make it more similar to the leading nanodistricts cluster rather than to the government-led nanodistrict cluster.

Remaining are 16 metropolitan areas that could potentially be grouped into a single cluster because of similarities in their nanotechnology research characteristics (i.e., the previously noted six-cluster solution). However, our seven-cluster solution distinguishes these cities into two clusters. The first (DIV) is composed of Dallas–Fort Worth; Philadelphia; Detroit; Research Triangle Park, North Carolina; Pittsburgh; Houston; Cleveland, Ohio; and Minneapolis. The second (FOC) is composed of Austin;

Phoenix; State College, Pennsylvania; Albany, New York; Atlanta; Gainesville, Florida; Madison, Wisconsin; and Seattle. The former group has more publications (but fewer on a per million population basis), more disbursed research activity with a lower median Herfindahl Index, more corporate publications, greater nanobiotechnology specialization, and more patents. The latter group has more of a university presence, a higher Herfindahl Index (even higher than the government-owned facilities cluster), more publications in the nanomaterials area, a higher percentage of publications in the later 2001 to 2006 time frame, and fewer patents than the former group.

Several summary findings emerge from this exploratory cluster analysis. First, U.S. nanodistricts are distinguishable not only by scale but also by organizational characteristics and specialization, research field concentration, and orientation toward the patenting of innovations. Second, although changes in thresholds can alter the number of clusters identified, reasonable solutions differentiate between a set of diverse polycentric nanodistricts (including New York, Boston, the Bay Area, Washington, D.C., and Chicago), more specialized polycentric nanobiotechnology clusters (Los Angeles and San Diego), and sets of monocentric clusters led by either dominant universities or leading government laboratories. Third, there is considerable nanotechnology research and innovation activity in locations recognized as prominent in prior rounds of technological development, including Boston and Silicon Valley. Yet there is also evidence of divergent nanotechnology-locational activity in other regions with concentrations of human capital and institutional investment. We expand on and discuss the implications of our findings below.

Conclusions

As an emerging technology, nanotechnology has attracted policy interest nationally and in many regions, including in well-established high-tech centers and in locations with high ambitions for improved standing in leading-edge research and technology-oriented business development. As we have noted, there is debate about whether nanotechnology will follow the regional path of prior rounds of emergent technologies. There is particular interest in whether the regional route of biotechnology—based on academic star scientists, spin-offs, and attraction of larger pharmaceutical and related industries—will be replicated. Meanwhile, policy makers in other locations hope that nanotechnology will offer fresh opportunities for additional regional entrants. Although the *use and deployment* of nanotechnologies in systems, products, and processes have the potential for economic benefit (not necessarily without economic and societal risk) in many sectors across almost all regions, these policy makers are keen to promote their regions as among the few that are prominent *creators and producers* of research and innovation in nanotechnology.

This study has found that there are multiple factors associated with the development of nanotechnology research regions that accommodate both the path-dependency course and the potential for emerging aspirants to become new centers for nanotechnology R&D. We emphasize that our findings primarily relate to the United States, although we observe that it would be insightful for future research to explore whether the results found for U.S. nanodistricts hold up in other locations where nanotechnology R&D is strong, such as Europe and Asia.

The literature on path dependency and cumulative advantage leads to the suggestion that nanotechnology will be concentrated in a small number of areas where previous rounds of technology have predominated and that have deep-rooted capabilities and diverse assets for developing and commercializing scientific innovations. We have found that this proposition has merit. Our analysis shows that Northern California's Bay Area (including San Francisco and Silicon Valley) and the Boston metropolitan area (including Cambridge and Route 128) are among leading U.S. nanodistricts in terms of research outputs and the diversity of institutional research sources. Chicago and the Washington, D.C., metropolitan areas are also in this group. Significantly, all the cities in this cluster (TLEAD) exhibit local commercialization potential with high numbers of nanotechnology patents and nanotechnology publications. New York is another leading region in nanotechnology R&D, although its position derives more noticeably from prominent corporate activities rather than from star scientists in universities. The presence of large and prominent corporate research labs has long been a strength of the New York region, but it may foreshadow an "Achilles heel" to the extent that large U.S. corporations (e.g., IBM or AT&T) downsize basic research investments in the future. Still, New York is likely to be resilient given that the region also has numerous universities, government labs, and smaller companies active in nanotechnology fields.

A strand of argument, consistent with a path-dependency perspective, suggests there will be an overlap between regions with strong prior specialization in biotechnology and those with current concentrations in nanotechnology. To explore this position, our study examined research field specializations in nanobiotechnology. We found that most of the nanodistricts profiled in the study were not overly specialized in nanobiotechnology, with two southern California exceptions. San Diego and Los Angeles (SCAL) are both more specialized in nanobiotechnology than are metropolitan areas in other clusters. San Diego and Los Angeles were previously found to be biotechnology centers by Cortright and Mayer (2002). This suggests that there may be some spillover between the prior prominence of these metropolitan areas in biotechnology and their current position in nanobiotechnology. However, the boundary between biotechnology and nanotechnology is both porous and hard to delineate, notwithstanding the effort made in our database-development search strategy to exclude biotechnology research that did not fall within the strictures of current nanotechnology definitions (refer to Porter et al., 2008). Hence, there is certainly overlap between the two fields that is captured in our data. At the same time, we did not find other biotechnology centers specified by Cortright and Mayer, such as New York, to be highly specialized in nanobiotechnology. One possible explanation is that in this latter set of nanodistricts, a large and diverse body of nanotechnology research is undertaken that overwhelms any clearly measurable biotechnology follow-on effect. Although there may well be specific university departments, faculty, or corporate researchers who are focusing on nanobiotechnology in other nanodistricts that have prior biotechnology prominence, there are also many researchers active in other nanotechnology fields these regions. Overall, we find the evidence is mixed in terms of support for the biotechnology-nanotechnology analogy in understanding the emergence of nanodistricts in our analysis.

In contrast to the path-dependency argument is the expectation that nanotechnology might be divergent in its regional trajectories, offering new opportunities to potential nanodistricts. Moreover, it was suggested that the development of human capital and facilities and institutional capital in the nanotechnology area might play a major role in facilitating this divergence. Our analysis focused on two measures of human capital in nanotechnology: scientific excellence (measured by highly cited research) and the extent of research collaboration and networks. In terms of highly cited research, most of the clusters identified in this study had similar levels of well-cited publications (using the threshold of 25 or more recent citations). However, the southern California cluster (Los Angeles and San Diego) was significantly higher in terms of highly cited research, with more than 20% of its articles surpassing the citation threshold. This cluster is specialized in nanobiotechnology and thus presents a profile that is consistent with previous research that has highlighted the importance of star scientists in the regional rise of biotechnology. Likewise, research networks appear to be particularly significant in the development of other nanodistricts excluding those in the early-era, university-dominated cluster and the New York region. The government facilities cluster has especially high numbers of multiauthor publications. This coupling of "hard" facilities with "soft" networking capabilities with other authors seems to be important in the development of these regions. To extend the implications of this finding, within the limitation of this analysis, large-scale research facilities may not be sufficient by themselves to develop a region into a leading nanodistrict without the combination of investments in extensive human capital linkages to exchange and diffuse new knowledge.

Our analysis probed the potential importance of organizational diversity in nanotechnology cluster development. Most of the clusters we investigated had a diversity of institutional sources involved in knowledge production. However, we found that the university and middle-focused clusters, and to a lesser extent the government cluster, had much of their publication activity contained within a single institution. We note that regions with nanotechnology aspirations but lacking existing standing as a high-technology center often focus their resources and efforts on a single institution. Our study suggests that, at least in the near term, a focused approach on facilities and human capital development at a single institution—be it a university or government laboratory—is associated with prominence as a nanodistrict. Mechanisms to achieve this include support for equipment, buildings, and leading scholars and opportunities to collaborate and network with nanotechnology researchers within and outside of the institution. The potential of nanotechnology across a range of scientific fields and applications allows room for established and organizationally diverse technological regions as well as more specialized regional nodes of excellence. However, a strategy of focusing nanotechnology facilities and human capital investments within a single institution, although a useful near-term step, may not be sufficient over the longer run. The focusing of nanotechnology R&D into a single institution may raise the capability and visibility of that particular organization and avoid duplication, but it also has the potential to crowd out other institutional actors who may be helpful in developing and energizing the regional cluster and who may exploit research avenues not favored by the dominant institution. In the long term, the most prominent technology clusters appear to have multiple nodes of institutional R&D strength, including commercialization activity. Current monocentric nanodistricts may be advised not only to strengthen intraregional (and external) R&D linkages and engage a full set of regional universities and public research institutions but also to give attention to strategies for commercializing their research and raising regional user-led business demand for nanotechnology-enabled applications and innovations.

Notes

1. The method described in this article builds on prior efforts to define nanoscience and nanotechnology, including Noyons et al. (2003).

2. Counts of publications and patents are treated as follows: A publication with multiple authors from the same institution is counted as a single publication, whereas an article with two authors from two institutions in different metropolitan areas is counted as two publications. Regarding patents, in most cases, the primary inventor's location is reported. Multiple inventor location is treated similarly to the approach used in the counting of publications.

3. The authors have produced an animated visualization of nanotechnology publication growth, by year, of U.S. nanodistricts, 1990 to 2006. This is available at http://www.nanopolicy.gatech.edu/maps.htm.

4. Nanobiotechnology was defined as publication records in the database that *combined* our nanotechnology search terms with these Web of Science subject categories: biochemical research methods; biochemistry and molecular biology; biodiversity conservation; biology; biophysics; biotechnology and applied microbiology; cell biology; developmental biology; entomology; evolutionary biology; genetics and heredity; marine and freshwater biology; microbiology; ornithology; parasitology; zoology; allergy; anatomy and morphology; andrology; anesthesiology; reproductive biology; cardiac and cardiovascular systems; clinical neurology; critical care medicine; dentistry; oral surgery and medicine; dermatology; emergency medicine; endocrinology and metabolism; gastroenterology; hepatology; health care sciences and services; health policy and services; hematology; immunology; infectious diseases; integrative and complementary medicine; medical informatics; medical laboratory technology; medicine, general and internal; medicine, legal; medicine, research and experimental; mycology; neuroimaging; neurosciences; nursing; nutrition and dietetics; obstetrics and gynecology; oncology; ophthalmology; orthopedics; otorhinolaryngology; pathology; pediatrics; peripheral vascular disease; pharmacology and pharmacy; physiology; psychiatry; public, environmental, and occupational health; radiology; nuclear medicine and medical imaging; rehabilitation; respiratory system; rheumatology; sport sciences; surgery; toxicology; transplantation; tropical medicine; urology and nephrology; and virology.

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