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SOCIO-ECONOMIC IMPACT OF NANOSCALE SCIENCE: INITIAL RESULTS AND NANOBANK

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ABSTRACT

Research on the nanoscale has revolutionized areas of science and has begun to have an impact on, and be impacted by, society and economy. We are capturing early traces of these processes in NanoBank, a large scale, multi-year project to provide a public data resource which will link individuals and organizations involved in creating and using nano S&T across a number of activities including publishing, patenting, research funding, and commercial financing, innovation and production. We report preliminary results from our work in progress. Nanotechnology is on a similar trajectory to biotechnology in terms of patents and publication, already accounting for over 2.5% of scientific articles and 0.7% of patents. Joint university-firm research is widespread and increasing. Regional agglomeration is also evident in both science and commercial applications, with the main clusters of firm entry by both new and pre-existing firms forming around major research universities publishing in nanoscience. Nanoscience has been highly concentrated in the United States, a few European countries, and Japan, but China has recently passed Japan in total articles per year and is beginning to have a significant number of highly-cited articles.

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Socio-economic Impact of Nanoscale Science: Initial Results and NanoBank

by Lynne G. Zucker and Michael R. Darby

Research on the nanoscale has revolutionized areas of science and has begun to have an impact, and be impacted by, society and economy. Early traces of these processes are already available to us, and we are capturing these data in NanoBank now before the ephemeral traces are lost to the social science and ethics research communities. NanoBank is a large scale, multi-year project to provide a data resource for social scientists, ethicists, nanoscientists, government officials, and the public. NanoBank will hold data elements that document the socio-economic impact of nanoscience and nanotechnology, and institutional change that occurs either to support the development or as a response to it. The research of the discovering scientists, those that learn from them, the non-profit organizations that assess risks and/or benefits of the new technology, and the process of industry formation will be documented. NanoBank traces the knowledge flows that underlie these changes, with special emphasis on cross-discipline flows and flows that transfer knowledge from discovering scientists to scientists working in firms. We begin the early part of the process of disseminating findings based on NanoBank in the Figures included in this report.

The U.S. government has identified nanoscience and nanotechnology as a scientific and technological opportunity of immense potential, formally launching a National Nanotechnology Initiative (NNI) in January 2000. It is difficult to define simply the full range of nanoscience, but the NNI's steering committee settled on a definition of nanotechnology that incorporates the scale ("approximately 1 – 100 nanometer"), the understanding, creation, and use of novel properties and functions that occur at the nanoscale, and the integration into larger scale assemblies.[1] Roco, Williams, and Alivisatos (1999), Siegel, Hu, and Roco (1999), Roco (2001), and Roco and Bainbridge (2001) provide a thorough review of the present state of nano S&T, the implementation of the NNI, and an introduction to thinking about the implications of nano S&T for our economy and society in the context of international developments in nanoscale research and commercialization.

Our Approach

"Technology transfer is the movement of ideas in people" (Donald Kennedy, Stanford University, March 18, 1994).

NanoBank is built on three insights into the processes of knowledge transfer, commercialization, and industry change. Turning first to knowledge transfer, scientific breakthroughs often yield new knowledge that is initially tacit – not yet codified. New codes and formulae describing breakthrough discoveries often develop slowly – with little incentive if value is low and many competing opportunities if high. This tends to keeps the knowledge tacit.

Second, those with the most information about breakthrough discoveries are the scientists actually making them, so there is initial scarcity: Scientists must learn the new knowledge from the discoverer or someone trained by the discoverer, limiting diffusion (Zucker, Darby and Torero 2002). The combination of scarcity and tacitness yields natural excludability, a barrier to the diffusion of the valuable knowledge. Indeed, cooperation by the inventor is required for successful commercialization by the licensee for 71 percent of the inventions licensed at

[1] Subcommittee on Nanoscale Science, Engineering and Technology (NSET), Committee on Technology, National Science and Technology Council, February 2000, full text can be found at http://nano.gov/omb_nifty50.htm.

universities (Jensen and Thursby 2001: Table 1, p. 243; see also Agrawal and Henderson 2002; Thursby and Thursby 2002.).

Third, commercialization of scientific breakthroughs requires access to naturally excludable knowledge, both tacit and scarce, that constitutes intellectual human capital retained by the discovering scientists. Thus, top scientists become the main resource around which firms are built or transformed in both biotechnology (Zucker, Darby, and Brewer 1998) and nanotechnology (Darby and Zucker 2003). Top discovering scientists who collaborate with company scientists have strong positive effects on company success that increases as the extent of involvement goes up (Zucker, Darby and Armstrong 1998, 2002).

Technological change at any given time is highly concentrated in a relatively few firms in a few industries (Darby and Zucker 2003a; Harberger 1998). This metamorphic progress dramatically transforms existing industries, forms new industries, or both. It is misleading to concentrate on the many firms in many industries achieving perfective progress through gradual improvement or inching up. To understand or affect technological progress we must focus on the exceptions – the industries and firms achieving metamorphic progress.

The source of the driving innovations for metamorphic change may be internal or external to the industry, with external innovations using different technological bases the most threatening to existing firms in a transforming industry (Tushman and Anderson 1986). Biotechnology transformed the pharmaceutical industry, and nanotechnology also uses different technological bases likely to transform industries – but it is too early yet to identify which industries will experience the largest impacts. In both cases, natural excludability of breakthroughs gives discovering and other top scientists and engineers a key role and increases the likelihood of metamorphic change.

In this paper, we report preliminary results based on core data files from an early pre-beta test form of NanoBank that focuses on nanoscale research and commercialization--an area with dramatic, recent breakthrough academic discoveries and evidence of likely metamorphic industry change. For purposes of comparison, we will refer to biotechnology that is a well-studied recent and continuing case of the development of a science-driven industry. In section I, we outline the central features of NanoBank and report on our current work identifying nanoscale search terms and phrases. We compare nanotechnology to biotechnology in the next section to motivate our approach and analyses. Section III explores the extent and geography of localization of nanoscience, including where and when firms are entering into nanotechnology and in what kinds of technologies. Section IV provides some comparison of the U.S. nanoscale science base with that in Europe, Japan, and some interesting recent developments in China (PRC). The final section of the paper presents a summary of the evidence and our conclusions.

I. NanoBank under Construction

Theory-based databases are not merely lists of variables and their related data, but build theoretically important relationships among variables that are predicted to alter the socio-economic impact of nanoscale research, as well as variables predicted to alter the socio-economic feedback effects on both the science and its commercialization Nanotechnology affects society, but society also affects nanotechnology. NanoBank is designed to provide the raw materials to conduct further research that can help understand and potentially guide the development and deployment of nanoscience and its commercialization, while simultaneously addressing basic processes of interest in social science.

NanoBank is designed as a data archive, an active site for exchanging papers and ideas for social scientists and ethicists, and a site for interdisciplinary learning across scientific disciplines through the construction of analogies and other methods. It will be located as one of the sites available from the NNIN portal, and also located as one of the resources available from the California NanoSystems Institute (CNSI at UCLA and UC Santa Barbara). [2] From design to launch in under four years requires rapid decisions and an active program of informing and engaging social scientists and ethicists likely to use this resource through professional organizations, national and local government agencies, and non-profit policy advisory organizations. We are also drawing in scientists who are crossing interdisciplinary boundaries, via analogies and other tools to aid understanding and use of concepts from other disciplines.

The research on social and ethical impacts will be facilitated by and, in many cases, enabled by NanoBank. NanoBank is an integrated database, which will be a public web-deployed digital library (DL). NanoBank links currently disparate data sets such as articles, patents, firm financial reports and directory listings, and university data. Thus, a nano or social scientist will be able to focus, for example, on articles and patents by a particular scientist through implementation by and success of a company or companies for which the scientist is a collaborator or officer. Alternatively, an ethics researcher will be able to locate all firms reporting research programs on products for which there are particular ethical concerns while another might quantify university to firm knowledge flows or patents, articles, and products resulting from particular research funding programs.

[2] Principal Investigators for the NSF funded NanoBank project are Lynne Zucker, Michael Darby, Roy Doumani, Jonathan Furner, UCLA, and Evelyn Hu, UCSB (SES 03074727).

NanoBank will also serve investors and firms seeking to allocate investment to promising new technologies, and policymakers attempting to assess the effects of alternative policy proposals. A NanoBank user might also seek all publications, patents, collaborations, alliances, and stock-price returns of firms working, say, on a particular use of carbon nanotubes and trace all academic publications and research grants in nano S&T tied to each firm involved in that use.

The key data elements that define the scope of content in NanoBank are outlined in Figure 1. Related to each one are a series of specific elements (variables). We cannot review those in detail here, but the searchable fields found at www.webofscience.com and at www.uspto.com, plus the text found at www.edgar.gov, provide some feel for the underlying richness of variables. To data at those sites we add links on specific variables within and between sites, such as linking patents and research articles by the same person and venture capital received and products in development by the same company. In fact, a key aspect of NanoBank is that we will build links, supervised by Darby and Zucker, between data elements that theory identifies as especially crucial to knowledge transfer and to productivity in both science and industry.

We include some elements in NanoBank designed to track interdisciplinary convergence across nano-, bio-, info-, cognio- areas of research and teaching (NBIC) and its outcomes in both nanoscience and nanotechnology. These elements are starred in Figure 1, and they range from a variety of interdisciplinary measures to tracking changes in departments and schools that reflect and institutionalize interdisciplinary boundary changes. Two main NBIC themes are addressed:

1) Track amount/quality of interdisciplinary research and training and timing/degree of new organizational structure that institutionalizes these changes, and the impact of this

interdisciplinary convergence on products and success outcomes, with additional coding of products by NBIC subarea (see Roco and Bainbridge 2002: Table 2, items B-F, p. 14).

2) Use of analogies/images of cross-discipline concepts to: (a) Communicate clearly across discipline boundaries (in part, to decrease tacitness and hence natural excludability) and stimulate discovery of new knowledge. (b) Facilitate borrowing of tools and other solutions across discipline boundaries, as in the new interdisciplinary area of computational biolinguistics.

NanoBank will also provide an important communication function for nanoscience and engineering generally, and for special initiatives such as the NSF National Nanotechnology Infrastructure Network (NNIN), through two archives on the site: (a) Vetted white papers dealing with nano science and engineering, business applications and issues, legal issues, and social and ethical impacts will provide a convenient source of reliable information for practitioners, other professionals, and an informed public; and (b) Preprints or links to preprints on an open basis subject to providing complete identification information on all affiliations and commercial interests; this information will provide early access to nano-relevant research.

Improved Methods Under Development: Science Growth by Broad S&T Area

We are experimenting with alternative specifications for computer identification of nanoscale articles. In this paper, nanoscale articles are identified by the union of these two (overlapping) text searches: (1) for the string "nano"; and (2) for any of 475 nanoscale-specific terms. All measurement terms are excluded. Some initial results are displayed in Figure 2 using a dataset of high-impact (very highly cited) articles from ISI. The nanoscale articles are categorized by a broad science and technology classification scheme (see classification details in Darby and Zucker 1999).

The number of articles rose initially most rapidly in semiconductors, but more recently the biology-medicine-chemistry and multidisciplinary categories have also seen dramatic growth. While the increase in information technology (IT) articles seems slight, other analyses not reported here show that, given the lower overall number of articles published in IT, the percentage increase is actually more dramatic than for the biology area.

As we develop new search strategies, we are benchmarking them against the *Virtual Journal of Nanoscale Science & Technology* (hereafter, *VJNano,* found online at www.vjnano.org). VJNano contains references to nanoscale articles published elsewhere as vetted by a distinguished scientific advisory panel of researchers actively working on the nanoscale. The search-based methodology used to produce Figure 2, discussed above, identify about 65 percent of the articles in VJNano. This provides one test of the degree to which search terms and phrases are able to identify recent nanoscale articles. With Jonathan Furner, we are combining these and other methods with information studies techniques to develop computer algorithms that use probability-based methods of discriminating between nano and non-nano.

II. Is the Growth of Nanotech Parallel to Biotech?

Comparing Nanotechnology and Biotechnology

Fundamentally, nanotechnology and biotechnology roots are in basic science and thus we expect their development to follow roughly similar trajectories. While there are a number of different ways to measure this, to begin the process we look at the rate of development of the scientific knowledge base as indicated by scientific publishing and the rate of knowledge capture as indicated by patenting. While publishing alone is sufficient to build the science-side of the process, establishment of intellectual property rights is necessary for much of the commercialization and its finance.

Figure 3 compares the remarkable increase in publishing and patenting that occurred during the first twenty years of the biotechnology revolution with what is occurring now in nano S&T. The Figure shows that the scientific and patenting growth of nanotechnology is of at least the same order of magnitude as biotechnology at a similar stage of development. We use 1973 as the base year for the start of biotech and 1986 for nanotech to compare them at similar points in their development (see the explanation of different years – and different methods of selection - below).

For articles, nano S&T is maintaining a growing lead over biotechnology articles. It is clear that nano S&T has burst upon the science and engineering scene a bit less suddenly than one would judge by the current notices. In terms of publications, rapid growth began about 1990. Since 1990 the growth in nano S&T articles has been remarkable, and now exceeds 2.5 percent of all science and engineering articles. Beginning in 1990, the percent of nano articles was significantly greater than the 1981-1989 mean and increasing every year.

Figure 3 also shows steady growth in nanotechnology patents as a percent of all patent issues. This growth is more dramatic considering that total patents also rise, increasing by about 150 percent over the same period. Actual counts of nano patents suggest a takeoff date for nanotechnology in the late 1980s. We observe that nanotech patents are ahead of biotech patents early in the process (through year 11) because very few patents were issued in biotech until the courts gave the go ahead in 1980. Thirteen years into the biotech revolution (1986), biotech patenting took off as: (a) gene sequences were patented with little proof of their use and (b) many variations on drug candidates were patented in an attempt to prevent quick competition from me-too drugs if one particular candidate were proved safe and effective.

Methods used in Figure 3: We identify nano articles using the text-search methodology described earlier, searching titles and abstracts for all articles in Science Citation Index Expanded through 2003 (Institute for Scientific Information 2003). Nano S&T patents are identified in the same way as nano articles, searching both title and abstract at www.uspto.gov. Biotech articles are defined in the figure as any that report a genetic sequence discovery (i.e., appear in GenBank), and this definition is conceptually overly narrow, but it has been proven in practice a very useful measure in our research on biotech. Biotech patents are defined through combining GenBank-related patents with the universe of biotechnology patents as identified by the U.S. Patent and Trademark Office on their published, cd-rom distributed data set.

Development of Base Years for Biotech-Nanotech Comparison: The Cohen-Boyer invention of genetic engineering (recombinant DNA) in 1973 is the conventional base year for biotechnology.[3] There is no consensus yet on the starting date for nanotechnology, but we will tentatively use 1986 as the base year based on the development of instrumentation that enabled manipulation of individual atoms and molecules at the nanoscale.

The atomic force microscope (AFM) was invented in 1986 by Binnig, Calvin Quate, and Christoph Gerber (1986); the AFM greatly broadened the range of materials which could be viewed at the atomic scale and enhanced the ability to manipulate individual atoms and molecules.[4] Haberle, Horber, and Binnig (1991) report a modified AFM for use on living cells

[3] Cohen, Chang, Boyer, and Helling (1973) and Cohen and Boyer (1980).

[4] The STM works by moving a very fine pointer back and forth over a surface with each scan line displaced slightly from the next, called raster scanning in reference to the parallel lines that

with which they observed the effects of antibody attachment and changes in salinity on living red blood cells. This built on earlier work developing the scanning tunneling microscope (STM) conducted at IBM's Zurich Research Laboratory in 1981 by Gerd Karl Binnig and Heinrich Rohrer (1982 and 1983); they received the Nobel Prize in Physics in 1986 for their STM work. The STM was the first instrument to enable scientists to obtain atomic-scale images and ultimately to manipulate individual atoms on the surfaces of materials.

Darby and Zucker (2003b) argue that such inventions of procedures or instruments – not exclusively the paradigm shifts famous from Kuhn (1962) – are the usual "inventions of a method of inventing" which set off major scientific and industrial transformations.[5] Instruments are particularly important because they effectively codify much of the "know how" involved in a breakthrough discovery making it possible for others to access and apply the new knowledge without directly working with the discoverers and their students. For a parallel example, consider the gene splicing machines that made discovery of new genetic sequences so routine that by 1988 graduate students at major research universities could no longer get a Ph.D. by reporting the discovery of a new genetic sequence.

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make up a television picture. A sensitive feedback mechanism maintains a constant distance relative to the surface so that a three dimensional representation is obtained. The STM could be used only on conductive materials (metals) due to the electron tunneling method used to maintain the constant distance between pointer and surface.

[5] Zvi Griliches (1957a, 1957b) was the first economist to study the class of breakthrough discoveries which he named an "invention of a method of inventing." His case was hybrid seed corn, a method of breeding superior corn for specific localities that effectively excluded farmers from reproducing the hybrid seed by saving part of their crop.

III. Geographic Concentration, Knowledge Transfer, and Firm Entry in Nanotech

There is concentration of knowledge in a few scientists and engineers who are pushing the frontiers of nano S&T and in the laboratories in which they work, just as metamorphic technological progress is concentrated in relatively few firms in relatively few industries. This concentration is a notable characteristic of previous scientific breakthroughs, especially those that involve a significant degree of tacit knowledge – art learned by doing with at the lab bench level. This tacit knowledge provides natural excludability that limits the diffusion of the new knowledge in cooperation with or even in the absence of explicit intellectual property rights of the discovering scientists and their organizations (Zucker, Darby, and Brewer 1998 and Zucker, Darby, and Armstrong 1998, 2002).

In Figure 4 as well as Figures 5, 6 and 7 that follow, we measure science base by number of nanoscale-related publications in the ISI World of Science database. This database contains all the ISI indexed-articles from 1980 through 2003 and nanoscale publications are identified by searching for nanoscale-specific terms in the title and abstract (when available), as explained above.[6]

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[6] The ISI database contains at least one research address and/or a reprint address except for 1.67% of the total observations. When the research address(es) is available, it is used as the location of the article and the reprint address is used when no research address is reported. If n different addresses are affiliated with the publication, we count 1/n article for each such affiliation.

Geographic Concentration: Figure 4 shows the geographic distribution of the nanoscience base in the U.S with respect to years and functional economic areas identified by the U.S. Bureau of Economic Analysis (BEA)[7]. Ten regions with most nanoscale-related papers (out of 172 BEA areas) account for 54 percent of the articles that has at least one coauthor with a US address. These 10 regions – New York-Northern New Jersey-Long Island, San Francisco-Oakland-San Jose, Los Angeles-Riverside- Orange County, Boston-Worcester-Lawrence-Lowell-Brockton, Washington-Baltimore, Chicago-Gary-Kenosha. Champagne-Urbana, Detroit-Ann Arbor-Flint, Raleigh-Durham-Chapel Hill, Philadelphia-Wilmington-Atlantic City – are notable for the strength in nano S&T of particular academic institutions and are not predictable by size, economy, or even overall strength of the science base.[8] As a further illustration of the concentration, almost 28 percent of all nano articles is accounted for by the top-3 regions (New York-Northern New Jersey-Long Island, San Francisco-Oakland-San Jose and Los Angeles-Riverside-Orange County.)

Knowledge Flow from Universities to Firms: When commercialization is occurring close to the scientific frontier, it is more likely that natural excludability is a significant barrier to knowledge transfer from discovering scientists to those who are applying the knowledge to develop commercial products. Under these conditions, characteristic of both nanotech and biotech, participation at the

[7] An address can be uniquely matched to a BEA area when the zip code is reported (which is the case in 95.56 % of the observations). When the zip code is missing, the city and state information were used to infer the BEA area, though in 2.21% of the cases resulted in multiple possible BEA areas. When m different BEA areas have been determined to be a possible match for an observation, each area is assigned 1/m the value of that observation.

[8] Compare these regions, for example, with the relative importance of high-tech states in Darby and Zucker (1999) and Zucker and Darby (1999).

lab bench level by top scientists who are making these discoveries is important to successful commercial application, necessary but not sufficient. Star scientist authorships of articles as or with employees of a firm were a potent predictor of the eventual success of biotech firms and Zucker, Darby, and Armstrong (2002) showed that counts of articles authored by firm employees with authors at top-112 universities had a significant (although smaller) impact on firm success.

To identify knowledge flows to firms in nanotechnology, we selected out all of the articles that include a firm in California as one of its addresses. All such articles (CA-firm articles) were then grouped into one of the five categories according to the other address reported for the same article. This is far from a simple process: variant names, non-standard abbreviations, and spelling errors make it difficult to determine the organization type. The categories are: "Firm Only" (for CA-firm articles that report only firms as addresses); "With University" (for CA-firm articles that have at least one university affiliated address); "With National Lab" (for CA-firm articles that have no university affiliation but has at least one national lab affiliation); "With Foreign" (for CA-firm articles that have no university or national lab affiliation, but has reported at least one foreign address) and "With Other" (for CA-firm articles that don't fall into any of the above categories.)[9]

In Figure 5 we see not only extensive and increasing publishing by scientist authors working in firms, but also a rising percentage of these are written in collaboration with scientists and engineers at universities. The university-firm knowledge flows represented by these articles indicate not only the natural excludability that makes the costs of close collaboration across university-firm

[9] Using all addresses reported in California, 95% were identified with a specific firm, university or national lab. The rest are mainly composed of federal and state government agencies and non-profit research institutions. Less than 5% have insufficient information to determine the organizational type.

boundaries worth incurring, but also the expected commercial payoff of nanotechnology. While Figure 5 is based only on California data at this point, we expect the results to replicate more generally.

Birth of the Nanotechnology Industry: Figure 6 illustrates the number of firms first publishing a nanoscale-related article in the ISI database by region and publication year with the firm's region based upon the address given by the author at the firm. Each time a firm first publishes an article in a given region is counted as an entry in that region regardless of whether or not the firm has already entered in another region. Hence, if an IBM Research Center in San Jose, California enters nanotech earlier than a second IBM Research Center – located in Yorktown Heights, New York – both the California and New York entries are reported in Figure 6 dated according to the years in which they respectively occur.

The regions that have the most firms entering overlap with the regions where most nanoscale articles are being written, except that San Diego, Denver-Boulder-Greeley and Minneapolis-St. Paul appear in the top 10 regions for firm entry.

Darby and Zucker (2003b) show that in a multiple-poisson-regression context both the number of highly cited articles published in a region and its average wage level (a measure of labor-force quality) are significant determinants of where and when firms enter nanotechnology. The effects of federal research funding to and nano articles by authors from top-112 research universities, regional employment, and total venture-capital flows are not statistically significant when all of these variables are entered in the same poisson regression, although these variables may be significant in regressions in which they are not competing with high-impact articles and/or average wages. It is difficult with small samples to measure separate effects of highly correlated variables such as high-impact articles (mostly authored by faculty with large federal research funding) and the amount of federal research funding. We expect some additional variables will be significant in future research when we can identify additional firms entering nanotechnology. The statistical insignificance of past venture capital flows is consistent with efficiency in that market.

There is in fact no census or widely accepted database to consult as to which firms are actively using nanotechnology in production or at least R&D activities – over the next few years, we plan for NanoBank to fill that and other information gaps faced by both researchers in nano S&T and those who study their impact. For now, the large number of articles ISI data base provide a means of identifying firms with a sufficiently deep involvement to be either publishing highly cited research articles or articles co-authored with professors from universities or both. Based on the patterns observed in biotechnology, few other firms without such ties are likely to become significant players.

IV. International Comparison

Figure 7 illustrates the international distribution of nano articles in the ISI database by year. Of articles written during 1980-2003, 72 percent have authors in one or more of the U.S., Japan, and the European Union.[10] China (PRC) was also added as a separate group to illustrate her remarkable improvement in recent years. Considering the whole period, the United States alone accounts for 29.15% of the world's nano articles, establishing the U.S. as the most dominant player in nanotechnology.

The data also suggest nano-related research becoming increasingly global throughout the last decade. Many countries that were not significant in 1980s and early 90s increase their

[10] The European Union articles are concentrated in Germany, France and the United Kingdom.

production dramatically. Other than China, which eventually caught up with Japan, countries like South Korea and India can also be counted as examples.

There was also a great increase in the number of countries that engage in nano-related research. While nano-related articles were produced in 43 different countries in year 1990, this number increased to 102 in 2003. Overall, almost 150 different countries were cited in the ISI articles in this time period. Both these factors cause a relative decline in the share of the U.S. nano articles, when compared to the initial stages of the nano technology improvement. Even so, more than 24% of the articles produced the world in 2003 were in the U.S., which is almost double the number by the next country, China.

Initial results adjusting for quality of research articles are shown in Figure 8. The distribution of high impact (very highly cited) papers in the world further reinforces the picture of U.S. dominance, but also shows that scientists and engineers in other nations are increasingly publishing high impact articles in the area of nanoscale research. China's great rise in nanoscience publications is evidence of a shift in effort, but her number of high impact papers remains low relative to the overall increase in publishing rate. Taken as a whole, these data confirm that the strength and depth of the American science base points to the U.S. being the dominant player in nanotechnology for some time to come, while the U.S. also faces significant and increasing international competition.

V. Summary and Conclusions

Nanoscale science and technology has all the earmarks of the kind of breakthrough metamorphic progress in which cascades of important scientific discoveries create the technological opportunities that transform existing industries and create new ones. We expect nanotechnology to account for a significant proportion of technological progress and economic growth over the next several decades. NanoBank will track these changes.

Nanotechnology is on a similar trajectory to biotechnology, stemming also from basic science breakthroughs, including important instrument invention relatively early in its development to codify part of the most fundamental tacit knowledge: scanning probe and atomic force microscopy, similar to the gene sequencing machines. However, much of the knowledge remains tacit in nanoscience as in bioscience and is best transmitted by working at the lab bench by one of the discoverers or someone trained by him/her, yielding natural excludability. As in biotechnology, we find that nanotechnology companies are founded when and where top nanoscientists are publishing. And we have also presented early evidence that the knowledge flow via collaboration in the lab is increasing between university scientists and company scientists, as indicated by co-publishing.

Regional agglomeration is also evident, with the main clusters forming around major research universities publishing in nanoscience. While there is considerable overlap with the biotechnology pattern, i.e. the relative dominance of the New York region and both Northern and Southern California, there are also significant differences that we believe are due to different resource-allocation decisions made in the past. The same is true at the national level: the U.S. accounts for over 55 percent of the highly cited articles on the nanoscale identified as "High Impact Articles" by ISI, while the U.S., European Union, Japan and China account for over 88 percent. So the concentration of nanoscale work is quite high internationally, similar to that found within the U.S.

It is too early to say where the most profitable commercial applications of nanotechnology lie. However, we can derive some early indicators from observing the pattern of areas in which firms enter nanotechnology, and over time decide to focus their efforts in product development, since both decisions are heavily conditioned by expectations held about eventual profits in different content areas of nanotechnology. Klevorick, Levin, Nelson, and Winter (1992) have emphasized that profitability is based on the appropriability of returns by the pioneer(s) as well as upon technological opportunity. Griliches (1957a, 1957b) argued that the earliest applications of an invention of a method of inventing are to those areas with the greatest expected profitability – now known as the lowest-hanging fruit. The low-lying-fruit theory suggests focusing for analysis of early industrial formation and transformation on the regions with the strongest science bases in areas where profitability is expected to be highest.

The race to apply nanotechnology to new products and services will be a long one. The growth and changes in institutions necessary to support this revolution, from supporting new institutes to dealing with cross-pressures between disciplines in interdisciplinary research, will determine part of the outcome. Interest groups operating in the nanotechnology field will alter what is done, when it is done, and how it is done – and possibly even whether it is done. Policy issues on many fronts are already confronting nanotechnology, and must be successfully addressed for nanoscale research and commercialization to grow and prosper.

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Figure 1. NanoBank.org: Examples of Defining Data Element Links [1]

Name of Person
Patent inventor
Article author
Principal investigator (PI)
Dissertation author
Dissertation chair
Officer/founder of firm
Science advisory board chair
Science advisory board member
*Coinventor, author, etc.

Discipline of Person
Department, curent or former [2]
Department of dissertation [2]

Date or Time
Patent application & grant dates
Article publication date
Grant/contract begin & end dates
Dissertation filing date
Dissertation filing date
Directory/database dates
Firm founding date
Firm nanotech entry date
Financial reporting dates
Initial public offering (IPO) date
Merger or alliance dates
Venture capital round dates
*Interdisciplinary team start dates
*Dept., institute, center entry/change/ merger date
*New interdisc. journal areas/start date
*Existing journal new discipline/area entry date
*Fed. Instit., IGA program start date
*Date of move between disciplines [3]

Organization
Patent assignee
Affiliation on article
Grant/contract recipient
University lists--NRC, IPEDS
Firm directory listings
Public firm databases (filings)
Financial market databases
Mergers & alliances database
Venture capital firm database
Investment bank database
Federal laboratory listings
Research institute directories
Organization's parent org. (if any)
*Non-profit directories, tax filings

Industry of Organization
Firm/university/fed lab/res. Inst.
SIC or NAICS industry codes
Venture Economics industry codes
*Nonprofit tax codes [501(c)(3), etc.]

Science & Technology Area Codes
US & International patent classes
ISI journal area
PACS codes/text
Nano S&T subareas (VJNano *et al.*)
Z-D broad science/tech area codes
*NBIC product codes

Geo-location
Patent inventor's address
Patent assignee's address
Author address
Grantee address(es)
Organization address(es)

Inputs, Outputs, and Success Measures
These can be measured at person, organization or sub-organization level and aggregated (as appropriate) based on: organization; city, state, region or country; discipline, industry, science/technology area, time; or combinations (e.g., by firm, region, and year)
Patent: counts, citations, claims
Articles: counts, citations
*Employment (& membership for nonprofits)
*Interdisciplinary Collaborations: counts, classifications, citations for articles and patents
Products in development: counts, classifications
Products on the market: counts, classifications
Venture capital: round counts, round values
Offerings: IPO value, later offering values and types
Investment bank reputation rankings
Stock price history
- Impact of risk assessment on stock price:
  - (1) Product failure, adverse event news
  - (2) NPO report, event news

Doctoral programs: ranking, graduates, faculty, funding
Awards: Nobels, NAS/NAE/IOM, Phi Beta Kappa, etc.
Grants/contracts: Federal, SBIR, ATP
*Interdisciplinarity
- *Cross-discipline co-chair on dissertation: counts
- *Cross-discipline co-authors, co-inventors: counts, citations, claims for patents
- *Cross-discipline firm officers, firm science boards: counts
- *Cross-discipline articles in old & new journals: counts, citations
- *Cross-discipline membership: depts., instits., centers, IGAs: counts

***NBIC Interdisciplinarity Convergence**
*Analogies/images of cross-discipline concepts
*New cross-discipline analogies/tools
*Cross-discipline teaching, patenting, research

Notes: * indicates NBIC elements
[1] Identify and search on specific terms in all NBIC areas.
[2] Non-academics: use former department or dissertation department.
[3] E.g., if dissertation discipline is different from department of first job.

Figure 2. High-Impact Nanoscale Articles by Major S&T Category, 1980-2001

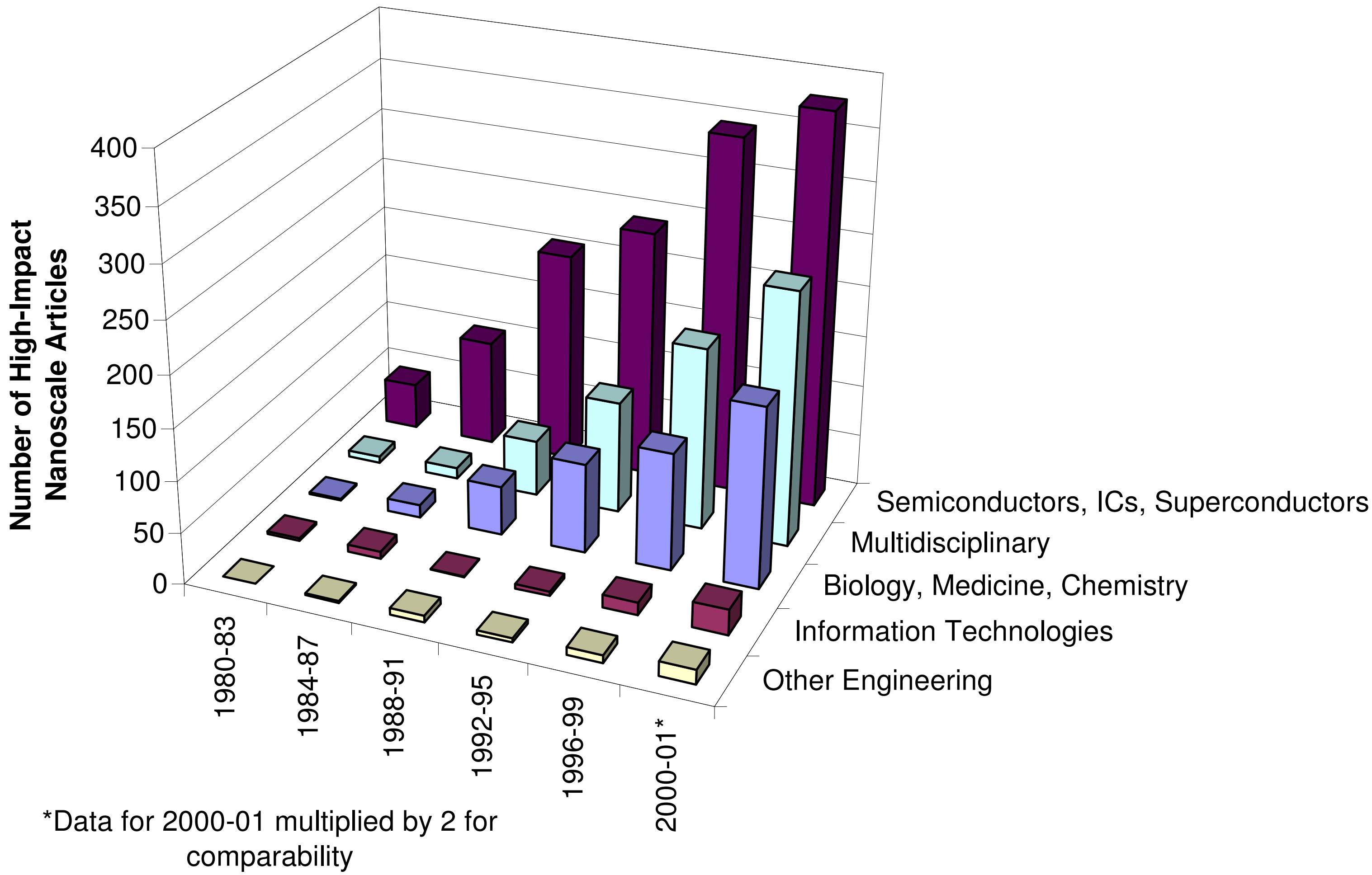


Figure 3. Comparing Nanotech (1986–2004) and Biotech (1973–1994) Publishing and Patenting Trajectories

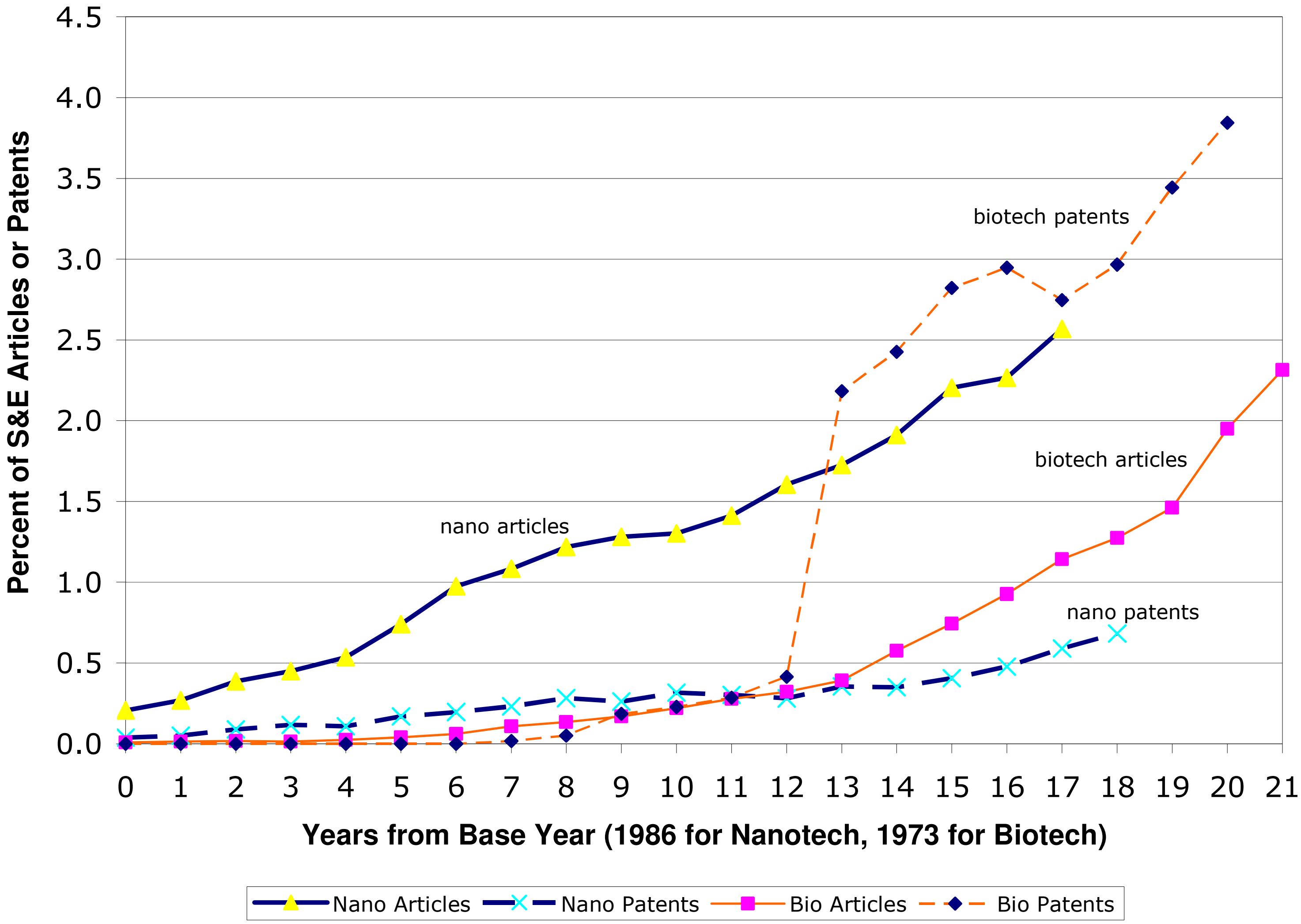


Figure 4. Nanoscience Geographic Concentration by Region, 1980-2003

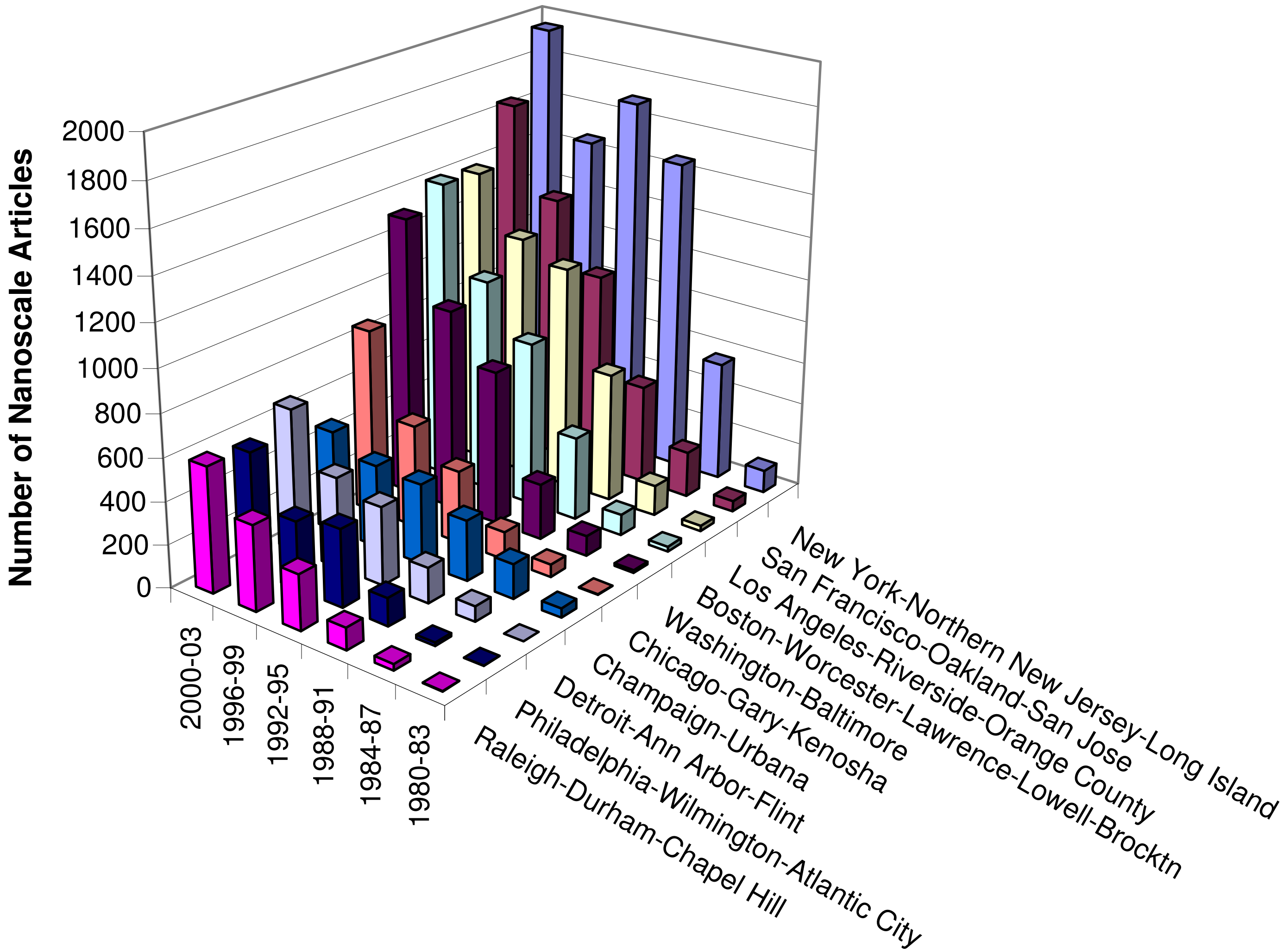


Figure 5. Tracing Knowledge Flow to Commerce:
California Firm Articles by Year and Co-Authorship, 1980-2003

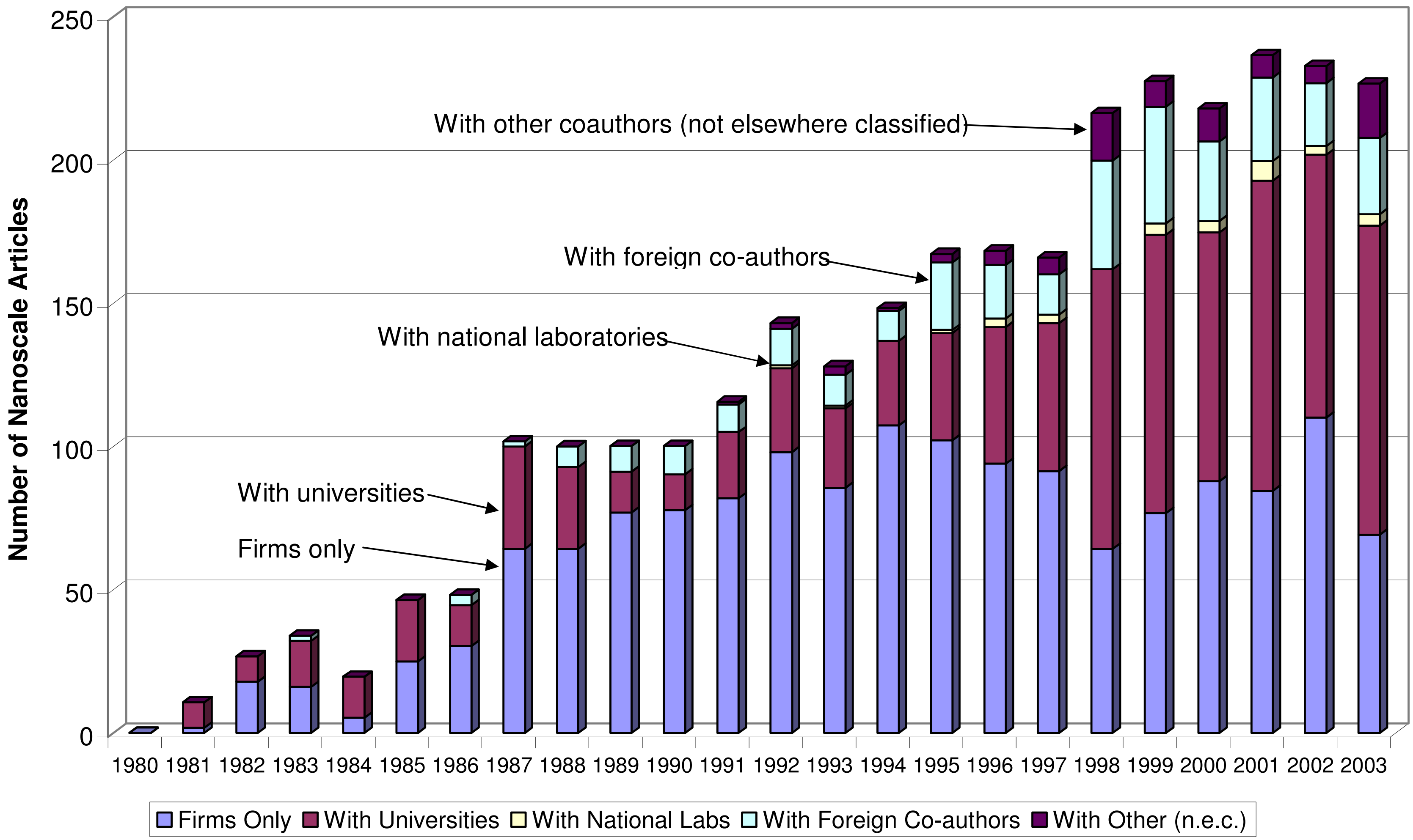


Figure 6. Birth of the Nanotech Industry by Region, 1980-2003

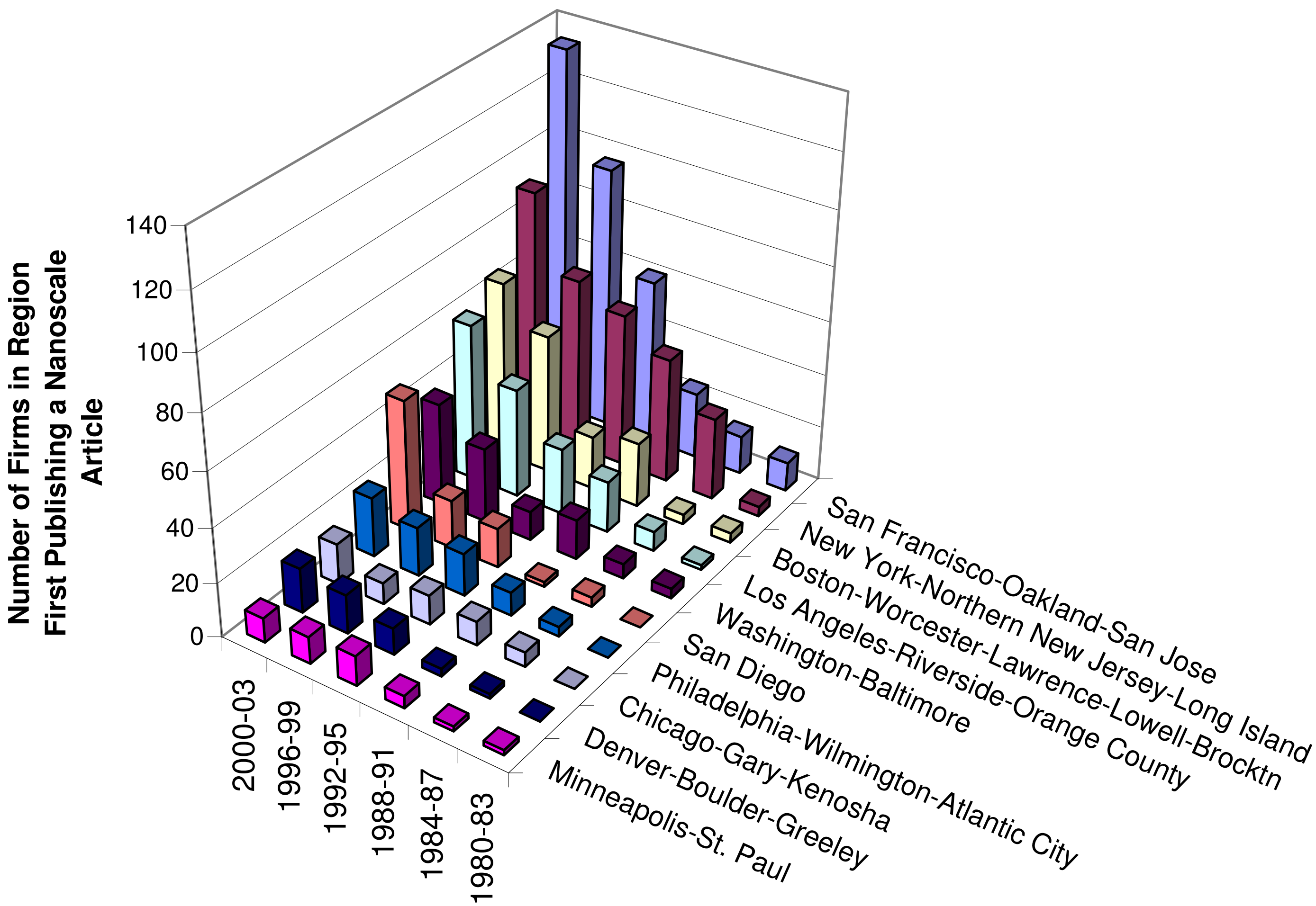


Figure 7. Nanoscience Geographic Concentration by Country, 1980-2003

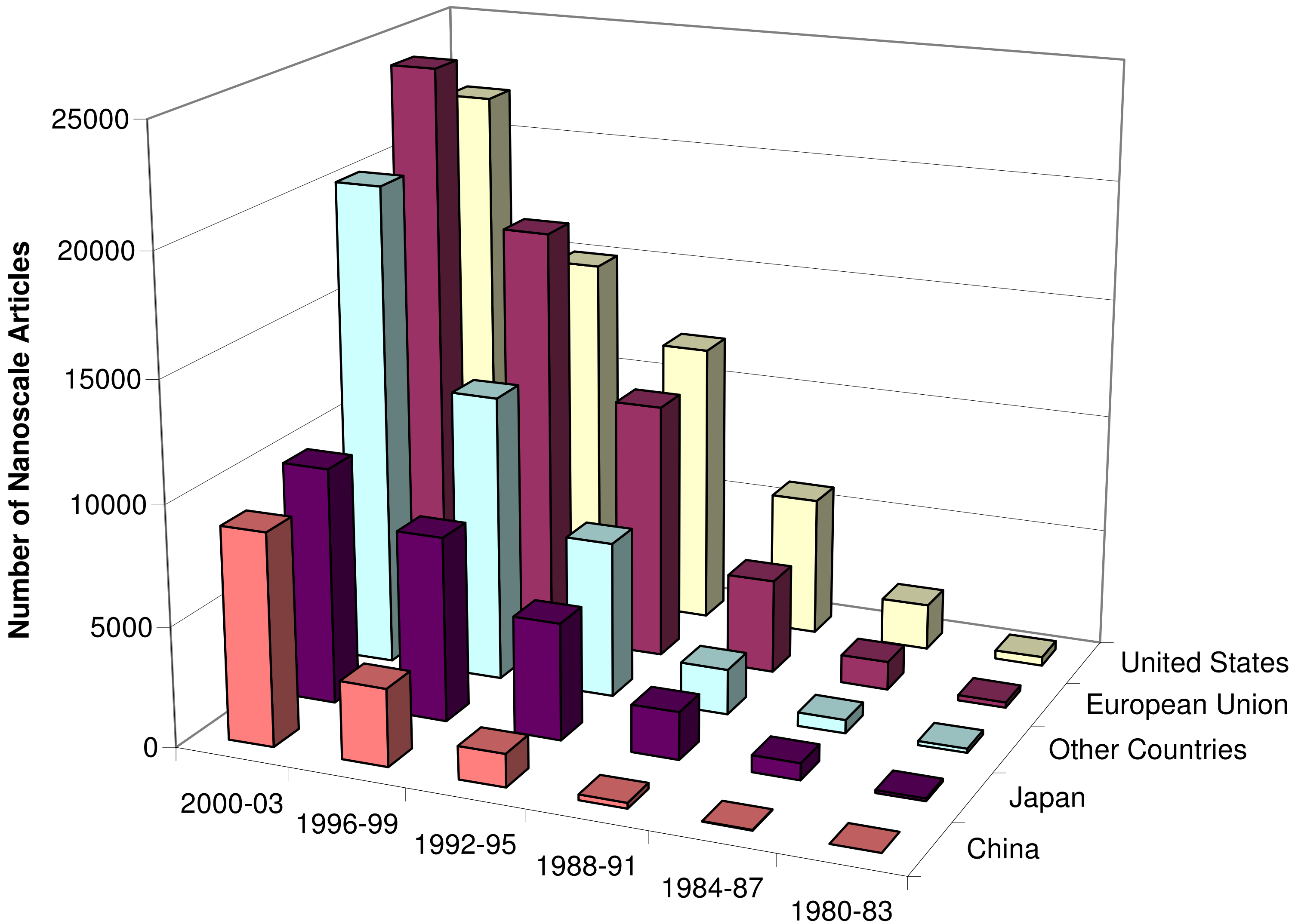
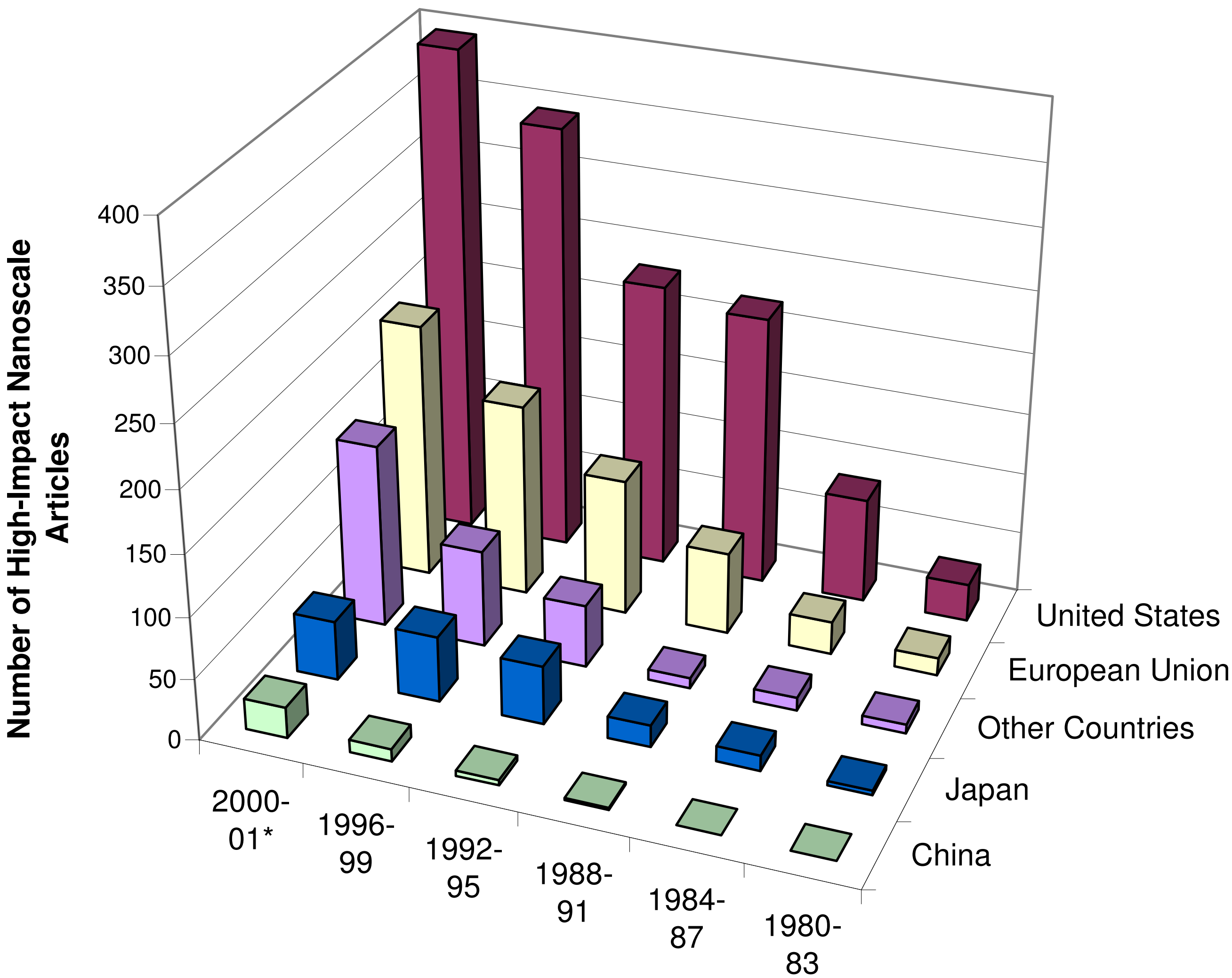


Figure 8. High-Impact Nanoscale Articles by Country and Quadrennia



*Data for 2000-01 multiplied by 2 for comparability