Technology in Society 34 (2012) 127–137

Contents lists available at SciVerse ScienceDirect

Technology in Society

journal homepage: www.elsevier.com/locate/techsoc

Knowledge production and nanotechnology: Characterizing American dissertation research, 1999–2009

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ARTICLE INFO

Article history:
Received 25 September 2011
Received in revised form 26 January 2012
Accepted 1 February 2012

Keywords:
Nanotechnology
Knowledge production
Higher education
Innovation
Bibliometrics
Research capacity

ABSTRACT

Understanding the emergence and evolution of nanoscience research is important for economic competitiveness and development as well as public policies concerning higher education and research and development. Assessing the emerging state of knowledge about nanotechnology is a significant step in enriching understandings of existing and future research capacities. To this end, we utilized bibliometric methods to characterize the profile and distribution of recent dissertations awarded at U.S. institutions. Our finding suggest that dissertations on nanotechnology experienced secular growth and were concentrated in engineering departments at established research universities and stimulated by federal funding. Finally, graduate research was geographically stratified and clustered in metropolitan areas with dense research infrastructures and ties to hi-technology industries. The implications for policymakers and social scientists interested in nanotechnology are assessed.

1. Introduction

Nanotechnology - a growing research field that involves re-engineering common substances at the nanoscale to create novel materials displaying emergent properties and functions- has received significant attention from firms, scientists and policymakers. While its potential remains uncertain, many observers believe nanotechnology will be a- if not *the*- critical technology in the 21st century. With implications for fields as diverse as water treatment, security, public health, agriculture, energy storage, and electronics and computing, several scholars predict nanotechnology's social, economic, and cultural consequences will be as profound and far-reaching as the steam engine, transistor, and internet [20,28,36]. In attempts to corner this emerging market several governments, including the US, China, India, Korea, Japan, France, and the UK, have invested billions in research and development (R&D), and identified nanoscience as a pivotal source of economic competitiveness and scientific development [3,4,11,12,29].

In mapping nanotechnology's growth and development researchers have employed a panoply of metrics including, *inter alia,* patents, academic publications, research collaborations, the foundation of start-up firms and research centers, and R&D funding [5,13,14,21,27,32,38,39]. One important indicator that has remained conspicuously opaque is dissertation production. Although data pertaining to graduate research in science and engineering is extensive (see [22,25]), it remains categorized by academic department and fails to capture nanotechnology, and other complex, interdisciplinary fields. While the authors feel these shortcomings provide sufficient justification for additional scrutiny, collecting and analyzing dissertation data also promises to deepen understandings of innovation by providing a valuable tool for forecasting trends, and gauging the effects of federal funding on research activities.

To correct the current scholarly neglect, this paper analyzes nanotechnology's developmental trajectory, and

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0160-791X/$ – see front matter
doi:10.1016/j.techsoc.2012.02.001

provides a comprehensive bibliometric study of dissertations awarded at American universities between 1999 and 2009. Additionally, our research examines the disciplinary, institutional, and spatial distribution of Ph.D. production, as well as, the effects of the federal funding on research activities. The results show that, as a research field, nanotechnology has experienced secular growth during the period in question. Growth was found to be significant when compared to related science and engineering fields both in general and at leading research universities. Moreover, when compared to other Research Level One (R1) universities, the rate of dissertation production was greater at institutions hosting research centers funded through the National Nanotechnology Initiative. Additionally, the evidence suggests that nanoscience has moved from a theoretical to applied phase with research shifting towards engineering subfields over time. Finally, the spatial distribution of doctorates is neither uniform nor random and- mirroring commercial activity- displays a high degree of geographic agglomeration in areas with pre-existing research and technical infrastructures- in this instance leading research universities. Weak patterns of diffusion indicate the existence of strong 'first mover' advantages, and path-dependent dynamics.

After discussing the significance of doctorate production as a metric of knowledge production and innovation, we describe in greater detail the data and methodology on which this study is based. Our results are presented in the following section and, to gauge the significance of our findings, are benchmarked against general trends in science and engineering. The concluding section provides a brief summary of our research and discusses its implications.

2. Knowledge production and Ph.D. data

If dissertations were of marginal importance for understanding innovation, the current lack of data would be of little consequence. However, as we argue, trends in Ph.D. production not only augment existing data, but also provide unique insight for studies of knowledge production and scientific discovery. While the creation of an original dataset for measuring Ph.D. research outputs (doctoral dissertations) is an important achievement on its own, by allowing scholars to track nanoscience research our study has several broader implications for intellectual and policy debates.

On the one hand, doctoral students compose over half of the staff at research university laboratories, and are a vital input in the research and patenting process, which for nanotechnology is most prevalent at the university level [35]. Thus, how graduate work in nanotechnology is spatially and conceptually clustered is likely to have significant spillover effects evidenced in economic activity and the foundation of start-up firms [1,2,33].

Second, by identifying innovators in the academic 'pipeline', dissertation data helps predict the future growth and distribution of the scientific labor force. This is especially true given that, at present, a doctoral degree is almost always required for nanotechnology related employment [34]. Currently, knowledge of these trends is constrained by insufficient data. According to Enders and De Weert ([10], 141): "reliable forecasts of scientific labor markets do not exist…because of the unavailability of reliable predictions of exogenous variables".

Finally, as they leave their academic institution to work in the academic, public, or private sector, doctoral students provide a critical vehicle in the inter-organizational circulation of experiential, embodied, and tacit knowledge [18]. Given that many graduate students in nanoscience and engineering fields come from countries other than that in which they are studying, their subsequent career trajectories can have an important influence on the global diffusion of both innovative knowledge and research practices.[1] Consequently, dissertation data provides an important resource for forecasting trends in the development of scientific and technical knowledge. While Ph.D. research provides a weak measure of innovation (versus patents and commercial products), it does provide a direct measure of early-stage innovative activity, and is particularly well suited to studying emerging technological fields- like nanoscience- that have yet to achieve significant market presence [1]. By providing a link between the established research community and future scholarly work, the profile of recent graduates intimately structures the intergenerational transmission of knowledge. In other words, young and emerging scholars are the foundation of tomorrow's research and scientific community: in the coming decades they will provide qualified workers, and many will play important agenda-setting roles as professors and research managers [18].

Given its significance for economic activity, labor force growth, and the transmission and diffusion of technical knowledge, Ph.D. production assists in mapping quantitative and qualitative shifts in the scientific community, and identifying sectors likely to experience surpluses and shortages of skilled knowledge workers.

In addition to its import for scholarship on science and technology, such data has significant policy implications. Establishing an index of nanoscience dissertation research enables governments, universities, and firms to more rigorously monitor and evaluate research capacities. Doing so would allow greater sensitivity in identifying extant strengths and weaknesses, and could be utilized to augment national and organizational strategies for future research planning and capacity building. Such strategies are of vital importance. In the present post-industrial climate, education, knowledge, and innovation are instrumental in brokering development, enhancing productivity, and remaining globally competitive in cutting-edge sectors.

3. Data and methodology

As recent scholarship attests, bibliometric methods provide an effective tool for mapping the introduction and evolution of new concepts, ideas, and technologies [8,24]. Given the dearth of specialized databases on the multi-disciplinary field of nanoscience, we constructed an

[1] According to NSF data released in 2006, the foreign student population earned 36.2% of the doctorate degrees in the sciences and 63.6% of doctorate degrees in engineering [19]. We plan to analyze both the contributions and career trajectories of foreign students studying nanoscience in a later paper.

original dataset by refining the publicly accessible records of the ProQuest dissertations and Theses Database, the most comprehensive repository of dissertations and theses produced in North America.

Numerous attempts have been made to study nanotechnology using bibliometric methodologies [15,26,32]. Unlike other science and engineering fields, the novelty and complexity of nanoscience evades existing disciplinary and conceptual categorizations. Consequently, the only effective way to assess nanoscience in bibliometric terms is through the use of Boolean search strings with keywords proven to identify nanotechnology related research. In this respect our research employed a modified variant of Kostoff et al's [15] widely accepted search-string to identify authentic nanoscience scholarship.[2]

Utilizing these search terms we created a spreadsheet of all nanoscience related dissertations granted between 1999 and 2009, a period defined by nanotechnology's formal establishment as a legitimate and critical research field, as well as, exponential growth in publications, patents, and start-ups [11,26,33].[3] After removing entries with institutional affiliations outside of the US, we were left with 4801 unique entries, which were subsequently coded by year, university, discipline, and zip code.[4] For each indicator, we determined whether the observed frequencies in our population were significantly different than the frequency one would expect given the overall composition of Ph.D. production in the U.S. science and engineering community. To accomplish this we employed a non-parametric 'goodness of fit test', in determining the chi-square statistic. We utilized the NSF's Integrated Science and Engineering Resources Data System (WEBCASPAR) to establish benchmarks concerning the disciplinary and institutional distribution of science and engineering Ph.D.s.

Additionally, in interpreting the impact of federal funding on research outputs, we compared dissertation production at R1 universities housing NNI-funded research centers with all other R1 universities.[5] The significance of differences in output and growth were determined using a two-sample t-test of means.

Before proceeding to our results two qualifications are in order. First, it should be noted that institutional variations in the determination of the time at which dissertations were awarded marginally impacts the number of dissertations recorded for each year. In several instances, universities consider doctorates to be awarded on the date the dissertation is defended, while others use the date the Ph.D. is filed, and a few use the date of graduation. In the later instance, if the dissertation is defended in the fall semester, official university reporting will differ by one year.

Further, there is an inherent lag time between when a dissertation is officially complete and when it is listed on the ProQuest database. While generally less than a year, in many instances this duration is longer.[6] Consequently, data for more recent years appears to be skewed as Ph.D. production grew consistently only to fall off significantly in 2008 and 2009.[7] Given that nanoscience research grew rapidly during this period, we believe such dynamics are an instance of delayed reporting rather than an actual decline. Faced with such constraints, we do not claim our analysis to be exhaustive, but rather illustrative for assessing research trends and identifying cumulative developments and accomplishments.

4. Results and analysis

4.1. Profile of dissertation production

To illustrate the trajectory of nanoscience doctorate production, we compiled and analyzed data from all US universities. Fig. 1 provides a dynamic picture of total nanotechnology dissertations awarded from 1999 to 2007. For reasons outlined above, the data from 2008 to 2009 are incomplete, and excluded from our discussion of temporal trends.[8] Dissertations identified as related to nanoscience grew by 538 percent, increasing almost exponentially, and outpacing total growth in science and engineering doctorates (see Table 1). Further, nanotechnology grew from 0.8% to 3.22% of all science and engineering dissertations awarded during the 8-year period (see Fig. 2).

This rapid growth is due, in part, to increased government funding for nanoscience and nanotechnology. As noted previously, since its implementation in 2000, the NNI allocated billions of dollars to multiple government agencies as a form of leverage for actively planning and orchestrating the research agenda of the American scientific community.[9] In particular, the initiative has

[2] When employing the search-string we searched the titles and abstracts of recent dissertations. Our search terms were as follows: NANOPARTICLE* OR NANOTUB* OR NANOSTRUCTURE* OR NANOCOMPOSITE* OR NANOWIRE* OR NANOCRYSTAL* OR NANOFIBER* OR NANOSPHERE* OR NANOROD* OR NANOTECHNOLOG* OR NANOCLUSTER* OR NANOCAPSULE* OR NANOMATERIAL* OR NANOFABRICAT* OR NANOPOR* OR NANOPARTICULATE* OR NANOPHASE OR NANOPOWDER* OR NANOLITHOGRAPHY OR NANOPARTICLE* OR NANODEVICE* OR NANODOT* OR NANOINDENT* OR NANOLAYER* OR NANOSCIENCE OR NANOSCALE* OR QUANTUM DOT* OR QUANTUM WIRE* OR NANOELECTROSPRAY* OR MOLECULAR WIRE* OR ((NANOMETER* OR NANOMETRE*) AND (FILM* OR GRAIN* OR POWDER* OR LAYER* OR DEVICE* OR CLUSTER* OR CRYSTAL* OR MATERIAL* OR MICROSCOP*)) OR ((SELFASSEMBL* OR SELF-ORGANIZ*) AND (MONOLAYER* OR FILM* OR NANO* OR QUANTUM* OR LAYER* OR MULTILAYER* OR ARRAY*)).

[3] The National Nanotechnology Initiative (NNI) was launched in 2000 with the initial participation of eight Federal agencies, and a 2001 budget of $464 million; it currently involves 25 Federal agencies, 15 of which have nanotechnology related R&D budgets. The 2012 Federal Budget provides $2.1 billion for the NNI (see http://www.nano.gov/about-nni/what).

[4] Data obtained from ProQuest's database included the following: author name; dissertation title; university; year; discipline; and field of study. Data pertaining to advisor/committee members, funding sources, and abstract and keywords, were unavailable. Despite these limitations the data assisted in providing an overall picture of the content and development of graduate research within the last decade.

[5] For a list of current universities designated as R1 see the Carnegie Foundation (http://classifications.carnegiefoundation.org/descriptions/basic.php).

[6] Based on correspondence with ProQuest representative.

[7] Our search, which was conducted in February of 2010, identified a steady increase from 158 nano-PhDs in 1999 to 850 in 2007, versus 741 in 2008 and 168 in 2009.

[8] Data for 2008 and 2009 are, however, included in our discussion of aggregate measures.

[9] The cumulative NNI investment (2001-2012) totals $16.5 billion (http://www.nano.gov/nanotech-101/nanotechnology-facts).

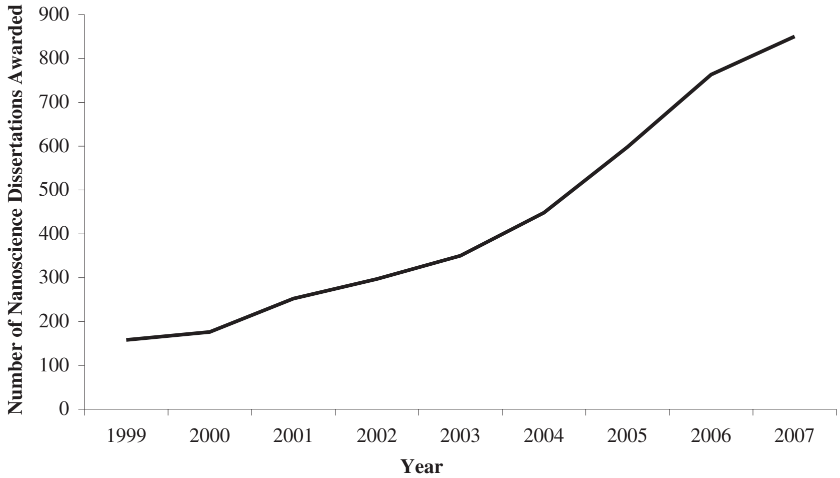

Fig. 1. Nanotechnology dissertations awarded in the U.S. 1999–2007.

Table 1
Growth in nanoscience dissertation production versus total growth in science and engineering.

Year	Percent growth	
	Nano	Total science and eng.
1999–2000	11.4%	0.2%
2000–01	43.2%***	−1.0%
2001–02	17.9%***	−3.8%
2002–03	17.8%**	3.0%
2003–04	28%***	5.7%
2004–05	33.5%***	8.8%
2005–06	27.6%***	9.0%
2006–07	11.4%	8.1%

Chi-square tests of observed and expected frequencies are used.
$^{**}P = 0.01$ or less; $^{***}P = 0.001$ or less.

emphasized advanced manufacturing, energy production and storage, electronics and computing, and biomedical research as critical areas of research [23]. In addition to national laboratories, corporate firms, and small businesses, the NNI has funneled millions into the university sector to "develop and sustain educational resources…and the supporting infrastructure and tools to advance nanotechnology" [23,4]. As our evidence indicates, this environment has created a host of incentives for promoting nanoscience research- a relationship that is tested through our analysis of institutional data.

4.2. *Institutional trends*

4.2.1. *Patterns of institutional concentration*

The number of dissertations awarded at academic institutions, and their share of the total educational output, provide basic indicators of the distribution of knowledge production across the national population of universities. As our data indicates, the precipitous growth in Ph.D. production has been concentrated within a narrow segment of research universities. While over 400 institutions award Ph.D.'s in the U.S., just 206 awarded dissertations on nanotechnology. Of these, nearly half were awarded at the just 25 institutions, and 15.6% of all Ph.D.s were granted at the five leading institutions of MIT, UC

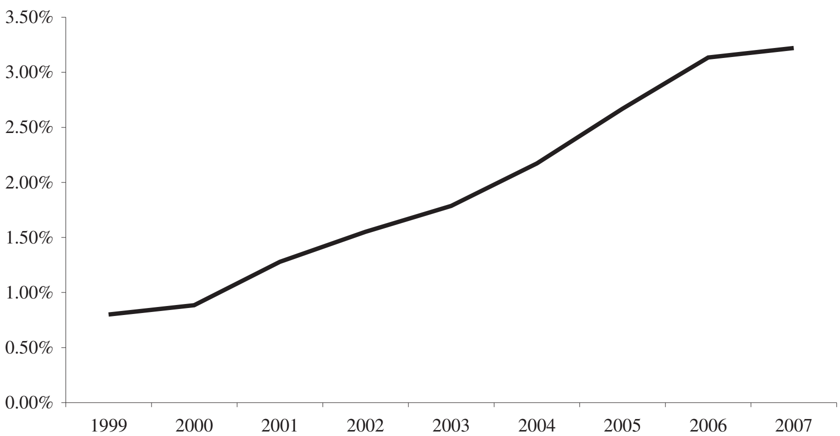

Fig. 2. Nanoscience PhDs as percent of all science and engineering doctorates, 1999–2007.

Table 2
Institutions with largest share of nanoscience dissertations 1999–2009.

Institution	Rank	No. PhDs awarded	Percent total awarded
Massachusetts Institute of Technology	1	184	3.83%
University of California, Berkeley	2	153	3.19%
Northwestern University	3	139	2.90%
Georgia Institute of Technology	4	137	2.85%
The University of Texas at Austin	5	136	2.83%
University of Illinois at Urbana-Champaign	6	117	2.44%
University of Michigan	7	106	2.21%
Stanford University	8	96	2.00%
University of Minnesota	9	95	1.98%
Cornell University	10	94	1.96%
Rice University	11	94	1.96%
University of California, Los Angeles	12	88	1.83%
Purdue University	13	86	1.79%
The Pennsylvania State University	14	85	1.77%
Rensselaer Polytechnic Institute	15	79	1.65%
University of Florida	16	78	1.62%
North Carolina State University	17	77	1.60%
Harvard University	18	75	1.56%
University of California, Santa Barbara	19	72	1.50%
Arizona State University	20	63	1.31%
University of Maryland, College Park	21	61	1.27%
The University of Wisconsin–Madison	22	54	1.12%
University of Massachusetts Amherst	23	54	1.12%
The Johns Hopkins University	24	53	1.10%
The University of North Carolina at Chapel Hill	25	52	1.08%
Total		2328	48.49%

Table 3
Institutional distribution of nanoscience doctorate production 1999–2009.

Institution type	No. of institutions	No. of PhDs	% Total nano-PhDs
All	206	4801	100.0
Largest	50	3332	69.4
Largest	25	2328	48.5
Largest	10	1257	26.2
Largest	5	749	15.6

Berkeley, Northwestern, Georgia Tech, and the University of Texas (see Tables 2 and 3).

Nanotechnology's visibility has grown considerably during the period in question. For the top ten institutions identified in Table 4, nanoscience's share of total science and engineering dissertations grew from 1.9% to 5.2% in 2007. These trends were most pronounced at Northwestern where nanotechnology constituted 9.9% of science and engineering Ph.D.s in 2007, and averaged 6.6% between 1999 and 2007.

Table 4
Nano-dissertations as percent of total science and engineering PhDs at the top ten nanoscience institutions 1999–2007.

Institution	Year									
	1999	2000	2001	2002	2003	2004	2005	2006	2007	Total/Average
MIT - No. nano-PhDs percent total	9	11	8	10	15	9	19	20	28	129
science - engineering PhDs	2.3%	3.0%	2.0%	2.5%	4.3%	2.4%	3.9%	3.9%	5.6%	3.3%
UC Berkeley	7	5	16	16	10	9	20	24	20	127
	1.6%	1.2%	3.6%	3.7%	2.1%	2.1%	4.1%	5.2%	3.5%	3.0%
Northwestern University	9	7	9	11	10	13	11	19	23	112
	5.7%	3.5%	4.5%	7.2%	6.3%	7.3%	6.0%	8.6%	9.9%	6.6%
Georgia Tech	8	6	8	7	3	13	12	27	28	112
	3.8%	2.8%	3.4%	3.0%	1.4%	4.5%	3.5%	7.3%	6.5%	4.0%
The University of Texas at Austin	2	3	7	8	12	11	18	25	34	120
	0.6%	1.0%	2.2%	2.6%	4.0%	3.4%	5.5%	6.4%	8.5%	3.8%
University of Illinois Urbana-Champaign	6	5	11	10	10	7	16	22	18	105
	1.6%	1.4%	2.6%	2.8%	2.6%	2.1%	3.9%	4.8%	4.1%	2.9%
University of Michigan	4	2	3	10	7	7	16	20	12	81
	1.1%	0.5%	0.9%	2.7%	1.9%	1.7%	3.6%	4.3%	2.4%	2.1%
Stanford University	3	2	1	7	12	7	15	15	17	79
	0.8%	0.6%	0.3%	2.0%	2.9%	1.8%	3.3%	3.3%	3.5%	2.1%
University of Minnesota	2	3	4	7	8	9	11	15	20	79
	0.6%	0.8%	1.2%	2.6%	2.6%	2.9%	3.0%	3.7%	4.5%	2.4%
Cornell University	3	3	8	5	10	10	13	13	11	76
	0.9%	1.0%	2.8%	2.0%	3.7%	3.5%	4.3%	3.8%	3.1%	2.8%
Total	53	47	75	91	97	95	151	200	211	1020
	1.9%	1.6%	2.3%	3.1%	3.2%	3.2%	4.1%	5.1%	5.2%	3.3%

Table 5
Ten largest sub-disciplines for nanoscience dissertations.

Institution	Total nano-PhDs 1999–2007	Percent growth 1999–2007	Total science and eng PhDs	Percent growth 1999–2007
UC Berkeley	127	185.71%***	4182	28.76%
MIT	129	211.11%***	3787	28.02%
Michigan	81	200%***	3698	34.42%
Stanford	79	466.67%***	3622	35.49%
Illinois	105	200%***	3521	19.84%
Wisconsin	47	350%***	3487	24.42%
Purdue	74	100%***	3106	33.23%
Minnesota	79	900%***	3145	32.45%
Florida	67	1100%***	3034	58.90%
Texas	120	1600%***	3020	11.98%

Expected frequencies were calculated based on growth in Science and Engineering PhDs at each institution.
***$P = 0.001$ or less.

Table 6
Comparison of nanoscience dissertations produced at research one universities.

	NNI-funded	Non-NNI
No. of institutions	37	47
Dissertations produced (Mean)***	62.6	26.9
Nanoscience PhDs as percent of total science and engineering PhDs (Mean)***	2.70%	1.60%
Growth in PhD production 1999–2007 (Mean)*	561%	450%

***A two-sample *T*-test at Alpha = 0.001 is used to test the significance of the difference in means. $P = 0.001$ or less.
*A two-sample *T*-test at Alpha = 0.05 is used to test the significance of the difference in means. $P = 0.391$.

To assess the strength of these trends we also analyzed rates of growth at the ten largest universities by total science and engineering doctorates (8 of these schools were also leaders in nanotechnology research). As Table 5

Table 7
Ten largest sub-disciplines for nanoscience dissertations.

Sub-field	Year		
	Total PhD 1999–2009	Percent of total	Percent growth between 1999–2007
Engineering, Materials Science	898	18.70%	524.00%
Physics, Condensed Matter	706	14.71%	182.50%
Engineering, Chemical	515	10.73%	1314.29%
Engineering, Electronics and Electrical	465	9.69%	480.00%
Chemistry, Physical	419	8.73%	236.84%
Engineering, Mechanical	325	6.77%	1540.00%
Chemistry, Inorganic	288	6.00%	278.57%
Chemistry, Analytical	228	4.75%	266.67%
Chemistry, Polymer	222	4.62%	244.44%
Engineering, Biomedical	130	2.71%	1066.67%
Other*	605	12.60%	546.67%
Total/Average	4801	100.00%	607.33%

*Note: Other includes the following sub-disciplines (frequencies are listed in parentheses): Agriculture, Food Science and Technology (5); Applied Mechanics (14); Atmospheric Sciences (1); Biogeochemistry (1); Biology, Animal Physiology (1); Biology, Cell (2); Biology, Microbiology (6); Biology, Molecular (5); Biology, Neuroscience (4); Biology, Physiology (1); Biology, Zoology (1); Biophysics, General (36); Biophysics, Medical (2); Chemistry, Biochemistry (43); Chemistry, General (15); Chemistry, Organic (118); Chemistry, Pharmaceutical (13); Computer Science (7); Education, Sciences (1); Education, Vocational (1); Engineering, Aerospace (9); Engineering, Agricultural (4); Engineering, Civil (11); Engineering, Environmental (37); Engineering, General (1); Engineering, Industrial (6); Engineering, Metallurgy (12); Engineering, Nuclear (4); Engineering, Packaging (2); Environmental Sciences (11); Geochemistry (4); Geology (1); Geophysics (1); Geotechnology (1); Health Sciences, Dentistry (1); Health Sciences, Pharmacology (8); Health Sciences, Pharmacy (16); Health Sciences, Toxicology (2); Mathematics (5); Physics, Acoustics (1); Physics, Astronomy and Astrophysics (1); Physics, Atomic (9); Physics, Electricity and Magnetism (15); Physics, Elementary Particles and High Energy (1); Physics, Fluid and Plasma (4); Physics, General (7); Physics, Molecular (15); Physics, Optics (92); Plastics Technology (5); Textile Technology (5).

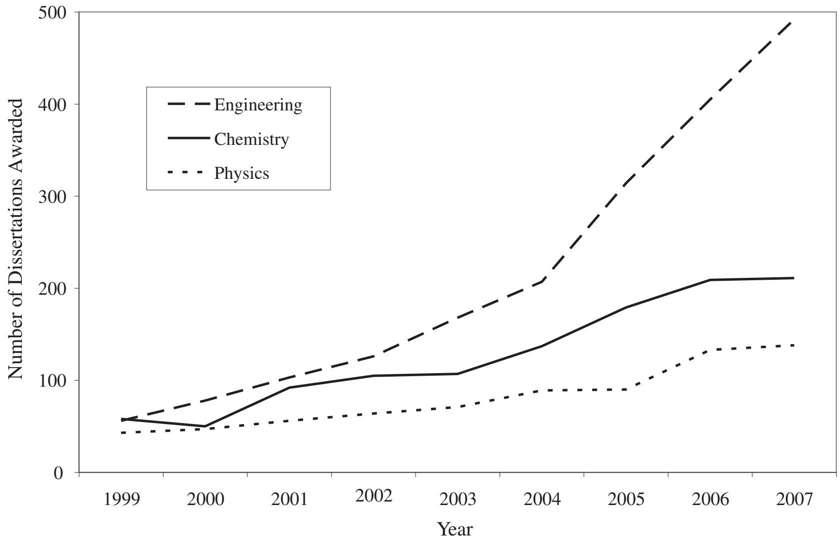

Fig. 3. Nanotechnology dissertations by discipline 1999–2007.

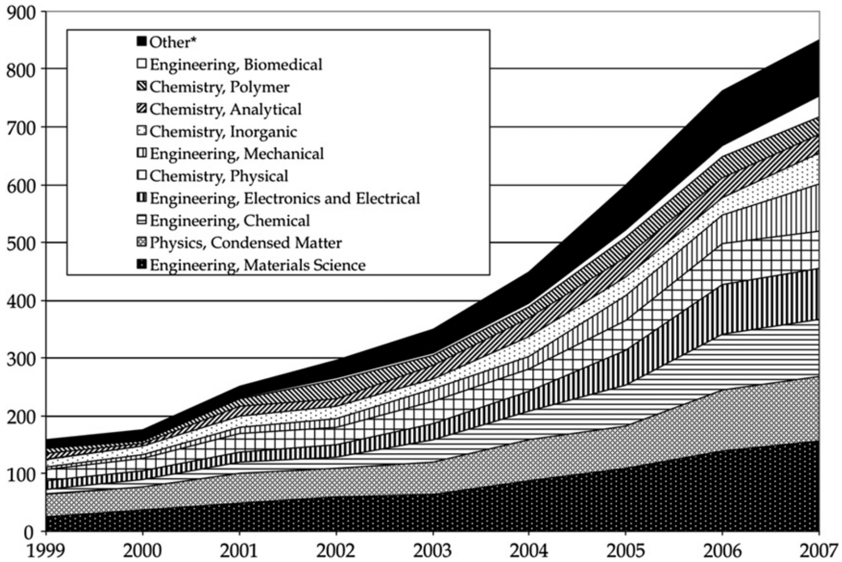

Fig. 4. Nano dissertation growth by sub-discipline 1999–2007.

indicates, nanotechnology dissertations grew significantly faster than would be expected when employing total growth in science and engineering as a benchmark ($p < 0.001$ for all).

Institutional trends also enable assessments of the influence of government funding and initiatives on the rate and distribution knowledge production. During the period in question the NNI, has provided hundreds of millions of dollars to university research. In increasing both the visibility of nanoscience, and creating new incentives and opportunities, the NNI's architects believed it would provide a vital stimulus in accelerating the "discovery, development and deployment of nanotechnology towards…the…national interest" [23,3].

To gauge its impact we compared Ph.D. production at universities with NNI-funded research centers with similar institutions that did not receive federal funding. To these ends we examined all R1 Universities with at least one dissertation produced between 1999 and 2009. Of the total 84 universities identified in our population [37], received federal funding through the NNI.[10] Universities receiving NNI funding accounted for 65 percent of the dissertations awarded at leading research universities. To control for scale effects we normalized nanoscience Ph.D.s as a proportion of total science and engineering dissertations. When controlling for institution size the effect of government funding remained significant: nanotechnology accounted for 2.7% of science and engineering dissertations at NNI-funded universities versus 1.6% for remaining R1 institutions. In both instances a two-sample *t*-test of means was preformed to determine whether government funding displayed a significant effect on the rate and prevalence of nano-scientific innovation. When employing an alpha of 0.001 it was revealed that differences were significant at the $p < 0.001$ level. Therefore we fail to reject the null hypothesis that government funding had no effect on graduate research. Differences in growth rates were also compared. When comparing all R1 universities with at least one dissertation published in 1999, NNI-funded schools grew at a rate of 561% versus 450% for the remaining institutions. However, a *t*-test at alpha 0.05 revealed these differences were not significant at the $p < 0.05$ level (see Table 6).

4.2.2. Disciplinary trends

This section examines the distribution of dissertation research by academic department and sub-discipline to further map nanotechnology's development and diffusion.

Table 8
Comparison of growth in nanotechnology PhDs and growth in related disciplines.

Disciplinary category	Nano-PhDs percent growth 1999–2007	General PhD percent growth 1999–2007
Science and Engineering	437%***	32%
Science	248%***	27%
Chemistry	262%***	9%
Physics	221%***	22%
Engineering	780%***	45%
Chemical Engineering	1314%***	37%
Electrical Engineering	513%***	63%
Materials/metallurgical engineering	478%***	45%
Mechanical engineering	1580%***	32%
Other Engineering	2500%***	40%

NOTE: (1) When comparing Broader Disciplinary Categoires (Science and Engineering, Science etc) dissertations produced in fields unrelated to nanotechnology (the social sciences, education etc) are excluded from our analysis. (2) For comparisons of subdisciplines only areas with at least one PhD recorded in 1999 were included in the above analysis.
Calculations based on the NSF's *Survey of Earned Doctorates* (SED). See http://www.nsf.gov/statistics/srvydoctorates/.
Chi-square tests of observed and expected frequencies are used. Expected values are calculated using general rates of growth displayed by NSF data.
***$P = 0.001$ or less.

[10] For a list of NNI-funded research centers see the initiatives website (http://www.nano.gov/html/centers/nnicenters.html).

The vast majority of doctorates awarded fell within the disciplines of engineering, chemistry, and physics. Together these three fields accounted for 98.2% of Ph.D.s completed between 1999 and 2009. Fig. 3 provides the total number of dissertations awarded within these fields between 1999 and 2007. While all three disciplines grew throughout the period, growth was most visible in Engineering where dissertation production expanded by 779% versus 264% and 221% for chemistry and physics respectively.

Table 7 provides a list of the ten largest sub-disciplines within our profile of recent dissertations. Together these areas accounted for 87% of all doctorates awarded. Work related to chemical, mechanical and biomedical engineering grew significantly faster than other leading subfields. Growth was less pronounced in physics-condensed matter, as well as, physical, analytical, and polymer chemistry- all of which displayed growth rates well below the average of 607%. In fact, while physics-condensed matter was the dominant sub-discipline in 1999- accounting for a quarter of

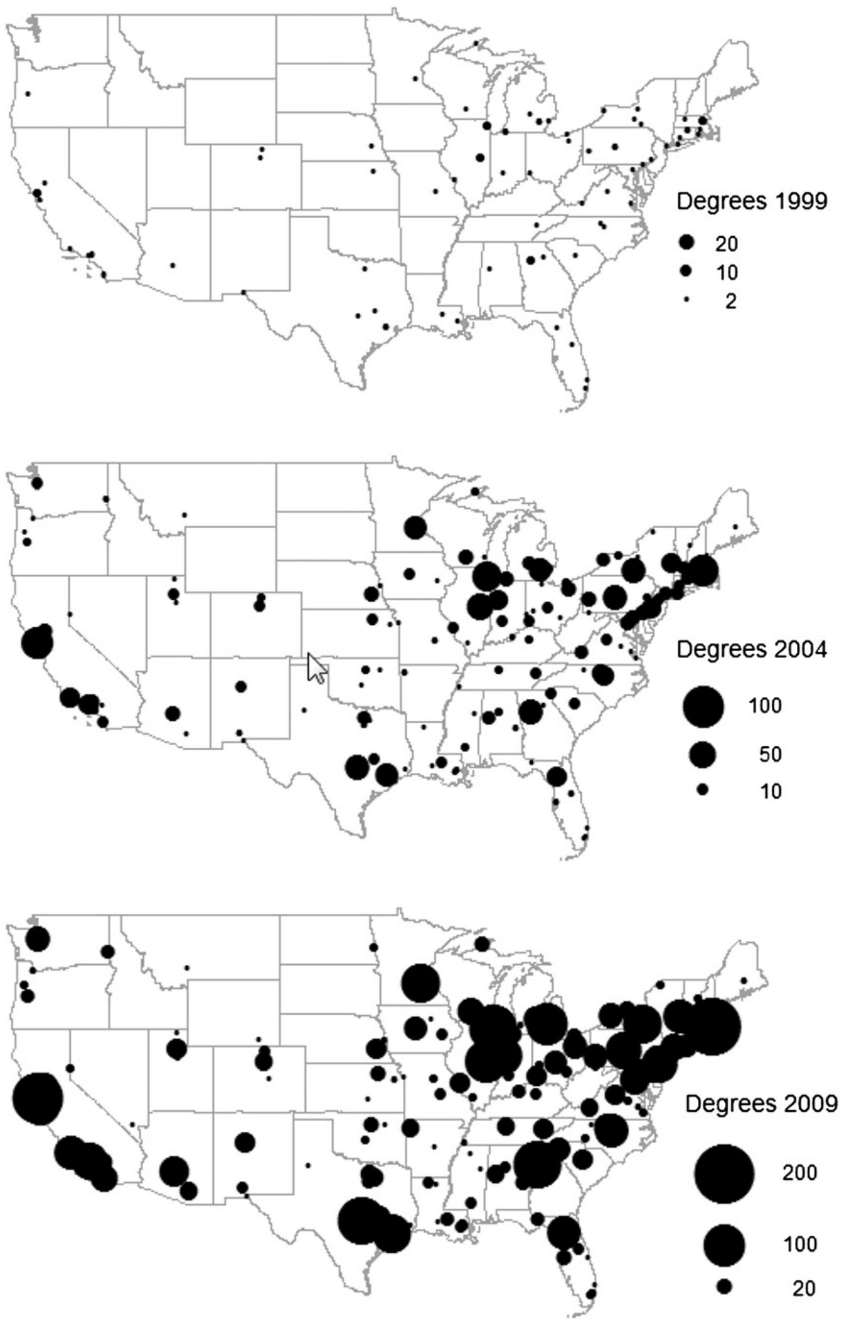

Fig. 5. Geographic distribution of cumulative nanoscience Ph.D. production 1999, 2004, and 2009.

Ph.D.s awarded, by 2007 its share fell to 13%, and was surpassed by materials science as the leading subfield (see Fig. 4). Together changes in the disciplinary and sub-disciplinary distribution of research reveal that, while remaining an important topic within the sciences where energy is largely devoted to experimental investigation and theoretical explanation, nanotechnology increasingly falls within the purview of engineering departments where the application of scientific and mathematical principles to practical ends is paramount. While warranting further scrutiny, these developments indicate that, alongside its perceptible growth, nanoscience is increasingly transitioning from a theoretical to applied phase.

Despite fluctuations in the prominence of particular fields, nanoscience dissertations significantly outpaced growth in their respective disciplines whether physics, chemistry, or engineering. This was also found to be the case for the subfields of materials science and chemical, electrical, mechanical, and other engineering (see Table 8). Chi-square tests reveal that in each instance the number of dissertations awarded was significantly greater than would be expected when employing general rates of growth as a baseline.

4.2.3. Spatial trends

In addition to the volume and content of research activities, scholars are interested in where technological innovation occurs [7,9,30,31]. In relation to nanotechnology, extant research presents two contrasting scenarios [33]. First, mirroring prior work on information and biotechnology, it is argued that nanotechnology will be defined by stratified and path-dependent distributional patterns in which research activities are focused in a small number of established innovation districts [39,40]. Here it is held that historically dominant research centers have significant ‘first mover’ advantages given pre-existing institutional assets whether significant funding, institutional support, or specialized facilities and equipment. Second, given nanotechnology’s uniquely multidisciplinary nature, and status as a platform technology with applications across a range of sectors, many believe the field will display broad and diffuse distributional patterns [17,33]. To adjudicate between these competing theories we offer a brief, and preliminary, discussion of the spatial distribution of nanoscience dissertations.

To analyze the locational configuration and diffusion of nanotechnology related research our data was coded by spatial identifiers (zip codes), and represented graphically to convey cumulative patterns of clustering. Additionally, the counts of dissertations were aggregated to the city or metropolitan area level as delimited by the US Census Bureau in 2000 (see Fig. 5). Our findings suggest that Ph.D. research is neither randomly nor uniformly distributed throughout the US. Specifically, the distributional patterns conveyed by our data lend support to claims of agglomeration and path-dependence. Although broadly distributed over 139 locales, nanoscience research is disproportionately concentrated within a few metropolitan areas. As revealed in Table 9 the top 10 metropolitan areas in 2009 - Boston, San Francisco-San Jose, Los Angeles-Long Beach, New York, Chicago, Raleigh-Durham-Chapel Hill, Atlanta, Austin-San Marcos, Champaign-Urbana, and Houston-accounted for 38% of all nanotechnology dissertations. Additionally, distributional patterns lend support for arguments of path-dependence and the emergence of ‘lock in’ effects. Table 9 reveals that 7 and 9 of the top 10 metropolitan areas in 2009 were also leaders in 1999 and 2004 respectively. Further, dissertation production has moved from a period of emergence to one of entrenchment. As displayed in Table 10 patterns of geographical concentration have coalesced over time with the distribution of Ph.D.s between leading metropolitan areas being identical

Table 9
Top ten metropolitan statistical areas (MSA) by cumulative nanoscience PhD production 1999, 2004, 2009.

1999			
Rank	MSA	No. PhDs	Percent total
1	Boston, Massachusetts-New Hampshire	14	8.86%
2	San Francisco-San Jose, California	10	6.33%
3	Chicago, Illinois	9	5.70%
4	Atlanta, Georgia	8	5.06%
5	Los Angeles-Long Beach, California	7	4.43%
6	Champaign-Urbana, Illinois	6	3.80%
7	Houston, Texas	5	3.16%
8	State College, Pennsylvania	5	3.16%
9	Hartford, Connecticut	4	2.53%
10	San Diego, California	4	2.53%
	Total	72	45.57%
2004			
Rank	MSA	No. PhDs 1999–2004	Percent total
1	Boston, Massachusetts-New Hampshire	105	6.25%
2	San Francisco, California	95	5.65%
3	Los Angeles-Long Beach, California	70	4.16%
4	Chicago, Illinois	69	4.10%
5	New York, New York	61	3.63%
6	Raleigh-Durham-Chapel Hill, North Carolina	57	3.39%
7	Champaign-Urbana, Illinois	49	2.91%
8	Atlanta, Georgia	49	2.91%
9	Austin-San Marcos, Texas	44	2.62%
10	State College, Pennsylvania	43	2.56%
	Total	642	38.19%
2009			
Rank	MSA	No. PhDs 1999–2009	Percent total
1	Boston, Massachusetts-New Hampshire	303	6.31%
2	San Francisco-San Jose, California	254	5.29%
3	Los Angeles-Long Beach, California	215	4.48%
4	New York, New York	203	4.23%
5	Chicago, Illinois	171	3.56%
6	Raleigh-Durham-Chapel Hill, North Carolina	155	3.23%
7	Atlanta, Georgia	147	3.06%
8	Austin-San Marcos, Texas	138	2.87%
9	Champaign-Urbana, Illinois	117	2.44%
10	Houston, Texas	117	2.44%
	Total	1820	37.91%

Table 10
Geographic concentration of nanoscience PhD production 1999–2009.

Leading MSAs	1999	2004	2009
Top 5	30%	24%	24%
Top 10	46%	38%	38%
Top 25	72%	63%	63%
All	100%	100%	100%

Note: Figures are cumulative.

in 2004 and 2009. Assuming future growth follows these trends, nanotechnology research will continue to be concentrated within a narrow segment of research or innovation districts.

5. Summary and conclusion

Advances in the state of knowledge have provided a significant force for economic development and socio-cultural transformation historically. Moreover, new useful forms of scientific and technical knowledge that underpin innovation have profound implications for labor markets, regional growth, international relations, and economic production and exchange. The importance of knowledge and human capital is uniquely applicable to the present. Unlike prior periods of industrial transformation where growth was predominantly limited by the availability of capital and industrial raw materials, currently the primary barrier to productivity is access to highly skilled labor and intellectual capital [6,16].

Acknowledging such dynamics, this paper has attempted to extend understandings of research on nanotechnology - a scientific field identified as a revolutionary technology with broad economic and societal implications. In particular it has utilized previously unanalyzed data on dissertation production to complement and enrich existing work on nano-scientific innovation. By analyzing the rate and institutional, disciplinary, and geographic distribution of dissertation completion this research not only identifies critical trends over the past decade, but provides an important window for assessing future trends related to innovation and economic and labor market development.

In sum, the preceding analysis demonstrates that doctoral research on nanoscale phenomena has experienced meteoric growth over the last decade, far outpacing growth in related fields. These trends are characteristic of nanotechnology's emerging visibility and substantive importance within the American science and engineering community. Further, this expansion has been uneven and is disproportionately concentrated in leading research universities and regions with significant research and technical infrastructures. Finally, the volume and rate of graduate research appears to be positively correlated with federal funding. Research universities housing federally funded nanotechnology research centers displayed higher rates of Ph.D. production and grew faster than equivalent institutions that did not receive such funding.

In short, while far from a definitive statement, our results provide several important measures for identifying the developmental paths- whether ideational, institutional, or spatial- nanoscience innovation is likely to follow. More than mapping innovative activity and gauging the effects of government funding, our findings can help improve understandings of America's capacity and competitiveness in this area. Given nanotechnology's profound societal and commercial implications, the importance of these efforts can hardly be overestimated.

As a final admonition, rather than an exhaustive account, the propositions advanced within this investigation are intended to generate discussion, reorient debates, and suggest new directions for subsequent research. Consequently, further empirical work is both desirable and necessary. Future research in the following four areas would be particularly fruitful. First, subsequent studies could further refine our data, and improve measures related to the substantive areas of graduate research. Here, rather than relying solely on disciplinary and sub-disciplinary categories, future work could provide a more fine-grained map of the conceptual and topical areas of study. Second, studies of graduate research outside science and engineering departments could provide a more holistic view of nanotechnology's status as an object of scholarly inquiry. Further, given that many topics central to technological innovation, use, and diffusion, whether risk perception, commercialization, or environmental health and safety, are often studied in the social sciences and humanities, such an approach could greatly improve our understanding of future trends. Third, studies based on international comparisons are desperately needed. Improving knowledge in this area would clarify what is distinctive to the American case, and amplify this study's findings by underscoring their significance in light of processes occurring in other national settings. Finally, studies of knowledge production and its implications for national innovation systems must remain attentive to the increasingly global character of American higher education. Specifically, as previously mentioned, degrees in science and engineering are often awarded to non-citizens who frequently return to their country of origin upon completing their studies. Future work must account for these trends and carefully scrutinize the mobility and globalization of the scientific community.

Acknowledgements

This material is based upon work supported by the National Science Foundation under Grant No. SES 0531184. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author and do not necessarily reflect the views of the National Science Foundation. It was conducted under the auspices of the University of California Santa Barbara's Center for Nanotechnology in Society (www.cns.ucsb.edu).

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