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

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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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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.