Barriers to the diffusion of nanotechnology.

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Abstract:

This paper provides the first empirical information about barriers related to the diffusion of nanotechnology, a general purpose technology. Our analysis is based on the findings from a state-wide survey of companies in North Carolina, USA. We find that the primary barrier is lack of access to early-stage capital, and the extent of this barrier is greater when the company contributes to the value chain for nanotechnology through R&D as opposed to through products or services. Another barrier is lack of access to university equipment and facilities, a problem greater in companies involved in nanotechnology research. From a policy perspective, our analysis suggests that state governments could act as venture capitalists to overcome market failure in the capital market, and that states could provide incentives to universities through public/private centers of excellence for sharing capital equipment and facilities with nanotechnology companies.

Keywords: nanotechnology | innovation | university partnerships | research funding | research partnerships | economics | research and development

Article:

1. INTRODUCTION

The 21st Century Nanotechnology Research and Development Act (PL 108-153; hereafter, the Act) was signed into law in December 2003 by US President George W. Bush. It authorized $3.7 billion in federal nanotechnology-related R&D spending over four years, starting in fiscal year 2005. Receiving broad bipartisan support in Congress, the Act put into law the programs and activities supported by the National Nanotechnology Initiative (NNI), one of the President's highest multi-agency R&D priorities.1 The Act formally made nanotechnology the highest priority funded science and technology effort since the efforts of the United States to win the ‘space race’ (Choi, 2003).

Although there is not a uniformly agreed upon definition of nanotechnology, the widely accepted NNI definition states that:

> [Nanotechnology refers to] the understanding and control of matter at dimensions of roughly 1 to 100 nanometers, where unique phenomena enable novel applications.[2]

The US government fostered the NNI, and hence the Act, in part because of the expected economic impact associated with nanoscale science and technology. While estimates of nanotechnology's economic impact vary widely across academic, government, and business experts – ranging from $1 trillion to $2 trillion in 2015[3] – most agree that its future potential is enormous.[4] According to the National Research Council (2002, p. 2):

> With potential applications in virtually every existing industry and new applications yet to be discovered, nanoscale science and technology will no doubt emerge as one of the major drivers of economic growth in the first part of the new millennium.

Widespread commercial adoption of nanotechnology is already growing rapidly, and early-commercial applications of nanotechnology have focused on improving existing products in such varied markets as cosmetics, coatings, textiles, and displays. Examples of areas in which nanotechnology is expected to have a high commercial impact in the future include improved chemical and biological sensors (within 1–5 years), new targeted drug therapies (within 5–10 years), and new molecular electronics (in 20+ years) (PCAST, 2005). The extent to which commercial potential in these areas is achieved, however, and the speed with which the United States achieves it, will depend in large part on the extent to which barriers to companies' adoption and integration of nanotechnology can be identified and then lessened.

Perhaps not surprising, given the recent origins of nanotechnology research, there is heretofore no systematic research on barriers inhibiting the diffusion of nanotechnology from the laboratory to commercial application. This void of information is troubling, especially from the perspective of economic growth. Nanotechnology, a general purpose technology as discussed below, is also a key element of technology infrastructure in that it is the foundation to the design, development, deployment, and use of other technologies and technology-based products and processes that are or could be central to the innovation process. This paper provides the first such information.

Based on data collected from a survey of the population of North Carolina companies already using nanotechnology, the paper identifies existing barriers and the extent to which they are perceived by survey respondents as inhibiting the future growth and competitiveness of their companies. North Carolina is one of the states in the United States long recognized as being among the leaders in high-technology research, development and commercialization and, thus, seems a good leading indicator of early prerequisites to the rapid diffusion of nanotechnology research (Luger and Goldstein, 1991; Link, 1995, 2002; Link and Scott, 2003; Fesler et al., 2005).

Section 2 presents a brief historical overview of US efforts to advance nanotechnology.[5] We discuss in Section 3 the population of nanotechnology companies in North Carolina and the methodology used to collect our survey information. Our statistical analysis is presented in

Section 4. In Section 5, we provide preliminary policy recommendations for ways to address diffusion barriers and enhance the adoption of nanotechnology.

2 US EFFORTS TO ADVANCE NANOTECHNOLOGY

The NNI serves as the US government's primary mechanism for supporting nanoscience research and nanotechnology development. Since its inception, the NNI's focus has been to develop an understanding of the novel properties that occur at the nanoscale and to harness the ability to control matter at the atomic and molecular level (PCAST, 2005).

2.1 Activities Setting the Stage for the Nanotechnology Act

Two motivations gave rise to the NNI. First, as mentioned above, nanoscale science and technology are predicted to have an enormous impact on the quality of life throughout the world. Second, at the time the NNI began there were no established major industrial markets for nanotechnology products. Government leadership and funds were deemed necessary to promote technology transfer activities to private industry by accelerating the time required for developing the infrastructure and technologies industry needs to exploit nanotechnology innovations and discoveries.

The NNI began long before the Act was passed. In early 1996, representatives from industry, government, and university laboratories convened to discuss the prospects for nanoscale science and technology. The attempt to coordinate at the federal-level scientific and technical work at the nanoscale began in November of that same year when staff members from six agencies decided to meet regularly to discuss their respective plans for programs in nanoscale science and technology. This group met informally until September 1998, when the National Science and Technology Council (NSTC) designated the group the Interagency Working Group on Nanotechnology (IWGN) under the White House Office of Science and Technology Policy (OSTP).

The IWGN laid the groundwork for the NNI by sponsoring numerous workshops and studies to help to define the state of the art in nanoscale science and technology and to forecast potential future developments in the field. Moreover, the group published reports on the state of the science between July and September 1999, including:

- Nanostructure Science and Technology: A Worldwide Study, a report based on the findings of an expert panel that visited nanoscale science and technology laboratories around the world.
- Nanotechnology Research Directions, a workshop report with input from academic, private, and government participants.

These two documents supported the IWGN efforts to raise nanoscale science and technology to the level of a national initiative by pointing up the current and potential future impacts of nanotechnology innovations and discoveries, respectively. According to Mihail Roco, Senior Advisor for Nanotechnology at the National Science Foundation (NSF) and primary author of the above reports, this was a crucial time for nanoscale science and technology (Bozeman and Boardman, 2004, p. 17):

> At that moment many looked at nanotechnology as science fiction. So we developed [the NNI] like a science project, from the bottom up. We started first of all to look at the fundamentals that would justify investment and not just to the smallness. We emphasized the new properties, the new phenomena where you have only a few mechanisms that could potentially revolutionize fields from medicine to electronics, as well as benefit society. It was a process to convince people. The NNI was not a decision at the political level.

In August 1999, IWGN drafted its first plan for a national-scale initiative in nanoscale science and technology. Both the President's Council of Advisors on Science and Technology (PCAST) and OSTP were involved in approving the plan.6 In January 2000, the White House officially announced its endorsement of the NNI and included the initiative in its 2001 budget submission to Congress.

To assist the Clinton administration convince Congress that the NNI should be a top priority, in February 2000 the IWGN prepared another report, National Nanotechnology Initiative: Leading to the Next Industrial Revolution, this time to supplement the President's budget request. The report highlighted the nanotechnology funding mechanisms developed for the initiative as well as the funding allocations by each participating federal agency. Moreover, it outlined nanotechnology goals and benchmarks, infrastructure requirements, and it contained examples of already-existing nanotechnology applications and partnerships that would become key components of the NNI.

After the February report, IWGN disbanded and the NSTC's Committee on Technology established the Nanoscale Science, Engineering, and Technology subcommittee (NSET) to fill IWGN's shoes.7 This ‘new’ group, which was chaired by Roco and comprised of the same people who staffed IWGN, drafted the NNI implementation plan, National Nanotechnology Initiative: The Initiative and Its Implementation Plan. NSET submitted this plan to Congress in July 2000, which was identical to the February report save new sections on interagency management objectives and coordination.

In November 2000, Congress appropriated $422 million for the NNI for fiscal year 2001, raising nanoscale science and technology to the level of a federal initiative. The subsequent activities paved the way to the formalized policies of the Nanotechnology Research and Development Act.

2.2 Events Subsequent to the Passage of the Act

Consistent with that focus, approximately 95% of the funding authorized by the Act was targeted to scientific R&D – roughly 60% for academia and 35% for government laboratories. Thus, by design, and consistent with similar national programs of this type, the NNI's primary purpose is to provide a strong R&D foundation from which industry can select technologies to exploit for commercial purposes.

Even with this strong focus on R&D, advancing nanotechnology commercialization remains a critical component of the NNI. Two examples clearly illustrate this point. First, The 2004 National Nanotechnology Initiative Strategic Plan (hereafter, the Strategic Plan), mandated by the Act, outlined the following four national goals:

1. Maintain a world-class research and development program aimed at realizing the full potential of nanotechnology.
2. Facilitate transfer of new technologies into products for economic growth, jobs, and other public benefit.
3. Develop educational resources, as skilled workforce, and the supporting infrastructure and tools to advance nanotechnology.
4. Support responsible development of nanotechnology.

Underlying the first three goals, particularly the second one, is a fundamental appreciation of nanotechnology's importance to the economy and the need to harness nanotechnology for commercial purposes.

Second, the Act charged the NSTC with developing a plan to utilize federal programs, such as the Small Business Innovation Research (SBIR) program and the Small Business Technology Transfer (STTR) program, to support commercialization of nanotechnology.8 Consistent with that charge, the Strategic Plan:9

> Encourage[s] agencies participating in the NNI to have components of their SBIR and STTR programs focused on nanotechnology topics, and in particular on nanomanufacturing…[and to]…Facilitate use of NNI-supported user facilities by small businesses that seek and receive SBIR and STTR grants and contracts.

In addition to these two examples, the Strategic Plan documented a number of current activities and plans to support the transfer of nanotechnology discoveries from the laboratory to commercial use. Among these are establishing industry liaison groups; supporting meetings involving industry, government, and industry; establishing and supporting user facilities available to researchers from all sectors; funding multidisciplinary research teams that include industry and university researchers; encouraging the exchange of researchers between universities and industry; establishing centers focused on nanomanufacturing research; and engaging with regional, state, and local nanotechnology initiatives.

Due to the brevity of the NNI's existence, efforts to assess how well it is meeting its goals have only recently begun (e.g. Bozeman and Boardman, 2004). In 2005, the PCAST undertook the first formal US federal government assessment of the NNI: The National Nanotechnology Initiative at Five Years: Assessment and Recommendations of the National Nanotechnology Advisory Panel (hereafter, the Assessment). The Assessment's executive summary stresses that (PCAST, 2005, p. 1):

> [The federal government's] substantial and sustained investment in nanotechnology has been largely based on the expectation that that advances in understanding and harnessing novel nanoscale properties will generate broad-ranging economic benefits for our Nation.

With respect to the NNI's progress on issues related to nanotechnology's economic impact, the Assessment found that several industrial sectors have a high and growing level of interest and investment in nanotechnology and are likely to outpace levels of national investment in the near future.

Nanotechnology is, or perhaps more correctly is expected to be, a general purpose technology (Youtie et al., forthcoming). A general purpose technology is an enabling technology, one that when adopted and used is expected to change production and consumption activity and behavior. Bresnahan and Trajtenberg (1995) argue that a general purpose technology has the following three characteristics: pervasiveness, an inherent potential for technological improvements, and innovational complexities that give rise to increasing returns to scale; thus, in a broad sense, general purpose technologies are part of technology infrastructure.10 And, over time, nanotechnology is expected to possess these characteristics.11 We argue that nanotechnology represents, in the form of a general purpose technology, a technology infrastructure, supporting the conduct of R&D and the application of innovations in production and in other technology-based activities. According to Davey (2003, p. 2):

> All natural materials and systems establish their fundamental properties at the atomic and molecular scale. Consequently, the ability to control matter at the shoes [nano] levels provides the means for tailoring the fundamental properties, phenomena, and processes exactly at the scale where the basic properties are determined.

In an effort to facilitate further nanotechnology transfer from the laboratory (company as well as federal) to the marketplace, the Assessment recommended two action steps beyond those outlined in the 2004 Strategic Plan (PCAST, 2005, p. 3):

1. The NNI's outreach to, and coordination with, the States should be increased.
2. The NNI should examine how to improve knowledge management of NNI assets.

These recommendations stem from PCAST's position that, while the federal government can take steps to help promote technology transfer, the primary responsibility for funding product manufacturing should be left to the private sector with appropriate assistance from state and local governments.

3 DATA COLLECTION METHODOLOGY AND SURVEY FINDINGS

At the end of 2005, the population of nanotechnology-based or nanotechnology-related companies in North Carolina totaled 40.12 With the assistance of the North Carolina Board of Science and Technology,13 the president (or his/her counterpart) of each company within this population of nanotechnology companies was asked to complete a pre-tested survey instrument related to, among other things, barriers to the diffusion of nanotechnology.14

Twenty-five of the 40 companies responded to the survey. This represents a 62.5% response. Figure 1 shows the location of each of the 40 companies in North Carolina in relationship to many of the state's universities with nanotechnology research centers. All but two of the companies in the population, one of which did not respond to the survey, are within 30 miles of at least one university-based nanotechnology research center.15

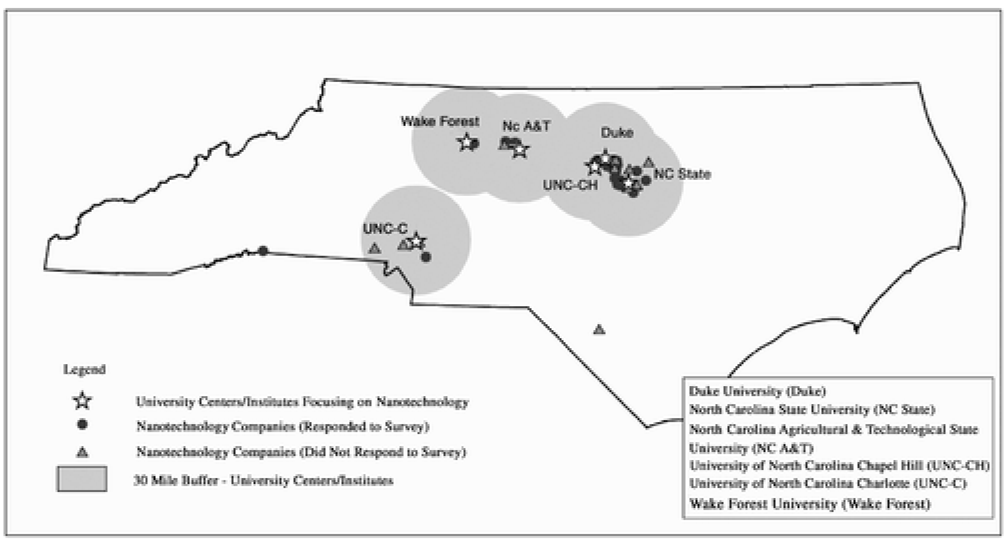

Figure 1. Population of nanotechnology companies in North Carolina.

Although not the focus of this paper, and thus not an issue in the empirics that follow, it is probably not coincidental that the vast majority of the nanotechnology companies shown in Figure 1 are juxtaposed to the state's research universities. Such location provides the opportunity for the acquisition of new knowledge – tacit knowledge in particular – and easier access to new innovations. The theory of agglomeration economics emphasizes such knowledge spillovers (Swann, 1998).16

The four survey statements that are the focus of this paper are in Table I and the mean responses (n=25) to each question are in column (2) of Table II. Overall, there was, on average, ‘agreement’ to each of the statements, but the greatest agreement was to the statement about access to early-stage capital. Access to early-stage capital being the greatest barrier is not surprising because nanoscience is not yet fully understood either in terms of its properties or capabilities for leveraging the commercialization potential of nanotechnology. As such, there are aspects of market failure in the capital market because of asymmetry of information regarding risk and return between a company and a financial institution.17

Table I Survey questions related to barriers to the diffusion of nanotechnology.Regarding the following selected factors for promoting your company's nanotechnology-based growth and competitiveness, please respond to the following statements using the response codes −3= completely disagree, −2= mostly disagree, −1= somewhat disagree, 0= neutral, +1= somewhat agree, +2= mostly agree, and +3= completely agree:‘My company could grow faster and be more competitive if it:

1. … had significantly greater access to university faculty who were doing research related to nanotechnology.’

2. … had significantly greater access to university nanotechnology-related facilities and equipment.’

3. … had significantly greater access to early-stage capital.’

4. … had access to a significantly more qualified – in terms of nanotechnology skills – labor force in North Carolina.’

Table II Descriptive statistics on the variables.

Variable	***Mean*** **(*n*=25)**	***Mean*** **(*n*=19)**	***Standard deviation*** **(*n*=19)**	***Range*** **(*n*=19)**
Barrier to Growth				
Access to faculty	0.88	1.06	1.59	−2 to +3
Access to equipment	1.20	1.22	1.52	−2 to +3
Access to early-stage capital	1.68	1.61	1.65	−2 to +3
Access to more qualified labor force	1.16	1.39	1.29	−2 to +3
RD	Na	0.67	0.49	0/1
Years	Na	3.94	4.12	1–15
NanoPct	Na	58.03	44.56	0–100
Emp (1000s)	Na	0.18	0.38	0.005–1
Rev ($M)	Na	3.89	0.46	0.025–20

From previous research (e.g. Feller and Roessner, 1995; Lee, 1996), we expected companies to perceive benefits from an association with a university – its faculty and especially its facilities (Santoro and Chakrabarti, 2001). Also, because nanoscience and nanotechnology are only in their infancy, qualified labor is an issue for at least some companies, especially small companies.

In the following section, we posit an econometric model to explain inter-company differences in the importance of access to the resources listed in Table I. We view a stated company's need for greater access to a resource as evidence that there is an existing barrier inhibiting an efficient diffusion of nanotechnology. Thus, the policy question raised by our findings is how to assist companies acquire these needed resources assuming that the existence of the identified barriers represents a market failure.

4 THE STATISTICAL ANALYSIS

To explain inter-company differences in the need for greater access to complementary resources to enhance the diffusion of nanotechnology and thereby facilitate greater nanotechnology-based growth and competitiveness, we posit the following model:

$$\text{ResourceNeed}_i = f(\text{RD}, \text{Years}, \text{NanoPct}, \text{Size})$$

where the variable (ResourceNeed i) represents the ith resource barrier that is inhibiting a greater diffusion of nanotechnology, i=1, 2, 3, and 4 based on the −3 to +3 Likert scale response to each of the four statements in Table I. The greater the value of (ResourceNeed i), the greater the relative importance of a company needing access to that ith resource.

The four independent variables in Eq. (1) represent selected company characteristics. Emphasizing these variables follows from various niches of economic and innovation theory, but their inclusion in the model in Eq. (1) is also driven by the availability of company-specific information. Estimating Eq. (1) will allow a description of the type of company that is facing a particular resource barrier, and thus substantiate policy recommendations to lessen barriers to the diffusion of nanotechnology.

RD is a dummy variable equalling 1 if the responding company's role in the value chain for nanotechnology is in research and development (as opposed to production of a product or service), and 0 otherwise.18 All else equal, R&D-based nanotechnology companies may have a differentiated need for resources than other companies farther down the supply chain, and thus may face skilled knowledge and specialized equipment barriers more so than general labor market barriers. To the extent that R&D-based nanotechnology companies have a greater absorptive capacity to utilize efficiently skilled knowledge and specialized equipment, they may have a greater demand for such internally lacking resources. The presence of skilled knowledge and specialized equipment barriers could imply a related need for early-stage capital. Thus, we hypothesize that the estimated coefficient on RD in the university faculty, the university equipment, and early-state capital equations to be positive.

Years is the number of years the company has been incorporating nanotechnology materials and/or methods into its activities, and thus it measures accumulated experience of the company with the technology and its underlying science base. Holding constant the stage of the company in the supply chain, experience could dampen the company's need for greater access to early-stage capital, but it could also enhance the company's need for each of the other complementary resources. Thus, we hypothesize that the estimated coefficient on Years to be negative in the early-stage capital equation but positive in the other three equations.

Finally, companies differ in the extent to which they are involved with nanotechnology. NanoPct is the percent of each company's R&D activities that incorporate or involve the use of nanotechnology-based materials and/or methods. Antonelli (2006, p. 211) noted:

> Localized technological change consists of creative adoption where external knowledge and embodied technologies are implemented with internal competence [emphasis added] and idiosyncratic knowledge acquired by means of learning processes.

Internal competence reflects, in part, the pervasiveness of a company's ability to adopt and effectively use nanotechnology. Thus, to the extent that NanoPct reflects such internal competence, we hypothesize a negative relationship between it and university faculty, university equipment, and labor resources. To the extent that such experience also dampens a company's need for early-stage capital, we hypothesize that the estimated coefficient on NanoPct in the early-stage capital to be negative.

A scale variable is also held constant in alternative specifications of Eq. (1).19 Size represents the size of the company, and it is measured alternatively as the number of employees (Emp) or total revenue (Rev) in year 2004.20 We offer no hypothesis about the impact of size on the existence of diffusion barriers.

Data on the four independent variables came from the company survey. Observations on some independent variables, such as Emp and Rev, are missing which reduces the sample size from 25 to 19. Descriptive statistics (n=19) on all of the variables relevant to the estimation of Eq. (1) are in Table II. And, the distribution of responses to the survey questions for the barriers to growth variables are in Table III.

Table III Discrete response profiles of the barriers to growth variables.

Variable	Distribution of responses						
Access to:	−3	−2	−1	0	+1	+2	+3
Faculty (%)	0	5.6	16.7	11.1	22.2	22.2	22.2
Equipment (%)	0	11.1	0	33.3	22.2	22.2	22.2
Early-stage capital (%)	0	5.6	5.6	16.7	16.7	5.6	50
More qualified labor force (%)	0	5.6	0	11.1	38.9	22.2	22.2

Note: Percentages may not sum to 100 due to rounding.

The ordered probit regression results from question (1) are in Table IV. We did not control for response bias to the survey for three related reasons. First, the only data that were available about the non-respondents was distance – miles to the nearest university. The mean distance for the sample of 19 responding companies was not statistically different from the mean distance for the sample of 6 non-responding companies. Second, there was no a priori argument to hypothesize why a company would respond or would not respond. And third, Figure 1 shows clearly that all but two of the population companies are within 30 miles of a university nanotechnology research center. We did test for non-linear effects in Eq. (1) but none were present; we also considered Emp and Rev entering logarithmically in Eq. (1), but while the sign pattern on these variables was the same as reported in Table IV, the level of significance was lower.21 Finally, Emp and Rev are highly co-linear – the correlation coefficient is 0.859 and highly significant – so each was considered separately in the estimation.

Table 4 is omitted from this formatted document.

Not all of our hypotheses are confirmed, but the results are nevertheless informative. R&D-based companies have a greater probability of completely agreeing (see the response scale in Table I) that access to university equipment and early-stage capital is a barrier to the diffusion of nanotechnology. The case studies of emerging technologies by Link (1996) and Link and Scott (1998) demonstrate that even the most experienced R&D companies rarely have sufficient equipment or complementary facilities to keep pace with the technology, and rarely are they willing to invest in such equipment or facilities until the technology becomes more mature.

Companies with greater nanotechnology experience have a higher probability of completely agreeing that greater access to university faculty is a barrier to the diffusion of nanotechnology, perhaps suggesting a minimum efficient level of internal knowledge is needed before accessing faculty expertise. If so, this would conform to evidence from previous studies of need and use of technical expertise.22 Hall et al.,'s (2003, p. 491) analysis concludes that university faculty are included in:

> …research projects that involve what we have called new science. Industrial research participants perceive that the university could provide research insight that is anticipatory of future research problems and could be an ombudsman anticipating and translating to all the complex nature of the research being undertaken.

Some internal resource base or experience base is thus needed for such university insights to be useful.

The more pervasive nanotechnology is within a company's operations the greater the probability of completely disagreeing that a barrier to the diffusion of nanotechnology is greater access to university equipment or early-stage capital. The latter finding is almost definitional because a company would not be in an early stage of technology development if the technology was pervasive. That the need for university equipment is not a barrier to the diffusion of nanotechnology in companies in which nanotechnology is more broadly utilized could be interpreted to mean that relevant scientific equipment is already in-house otherwise nanotechnology would not be so broadly utilized.

Finally, there is only very weak evidence that, in smaller companies, the probability of completely disagreeing that access to early-stage capital is a barrier to the diffusion of nanotechnology. And, regardless of the size of the company, access to a qualified labor force is not systematically a barrier to the diffusion of nanotechnology.

5 CONCLUSIONS

Although the empirical findings in Table IV represent the only quantitative information about barriers to the diffusion of nanotechnology, they must nevertheless be interpreted very cautiously. Mitigating the fact that we surveyed the population of nanotechnology companies in North Carolina, we have no way to determine if the population of nanotechnology companies in North Carolina is representative of the national population.23 And, we lack information about the non-responding companies in the population of North Carolina nanotechnology companies

In fact, what we do not know about each company may be more important than what we do know. For example, we do not know if a company is a university spin-off (Libaers et al., 2006). If it is, it could view access to university faculty and equipment differently than a company that is not (Steffensen et al., 2000). Also, we have no information about how effectively a company utilized its existing nanotechnology intellectual property and process technology. A company that is more efficient in its use of the extant technology could also view access to university faculty and equipment differently especially if the company utilizes university faculty to help it overcome technology-based research problems and especially at the basic end of the R&D spectrum (Hall et al., 2003).

With these caveats in mind, we offer two specific recommendations to ameliorate barriers to the diffusion of nanotechnology that follow from the findings in Table IV. First, there is a market failure in the capital market because of asymmetry of information about the risk and return associated with the adoption of nanotechnology and its impact on commercialization. While policy makers cannot solve this problem, state governments could act as venture capitalists in this regard in much the same way as the SBIR program acts as venture capitalist for agency-needed technologies. The step would not be unprecedented inasmuch as some states, most recently the State of Ohio (2005), have already developed legislation to permit state government venture capital funding. Second, states could provide incentives to universities for sharing capital equipment and facilities with nanotechnology companies. Such a policy effort would likely raise issues as to why nanotechnology and not some other burgeoning technology. One way to counter that argument is, say, for states to establish at public universities public/private partnership centers of excellence whereby new equipment is provided by the state with an understanding that its use is to foster partnerships with the private sector. Such activity would be in line with existing state policies in the many centers of excellence programs (Plosila, 2004).

Additional policy prescriptions await the emergence of more quantitative information about the economic impact potential of nanotechnology, in general, and the diffusion of nanotechnology, in particular. In the United States, early activities seem to indicate a continuing strong role not only for the federal government but also many state governments.

Notes

1 The NNI was promulgated in FY 2001 as part of the Clinton administration's efforts to raise nanoscale science and technology to the level of a federal initiative.

2 ‘Encompassing nanoscale science, engineering and technology, nanotechnology involves imaging, measuring, modeling, and manipulating matter at this length scale’ (http://www.nano.gov/).

3 The $1 trillion estimate is from the National Science Foundation; the $2 trillion estimate is from Lux Research.

4 Zucker and Darby (forthcoming) provide technology-based information (e.g., patent activity) to support indirectly this conjecture.

5 The section was prepared with the assistance of Craig Boardman (Bozeman and Boardman, 2004).

6 PCAST was originally established by President George Bush in 1990 to enable the President to receive advice from the private sector and academic community on technology, scientific research priorities, and math and science education. The organization follows a tradition of Presidential advisory panels on science and technology dating back to Presidents Eisenhower and Truman. Since its creation, PCAST has been expanded and currently consists of 23 members plus the Director of the Office of Science and Technology Policy who serves as the Council's Co-Chair. The council members, distinguished individuals appointed by the President, are drawn from industry, education, and research institutions, and other nongovernmental organizations.

7 The purpose of the Committee on Technology is to advise and assist the NSTC in improving the overall effectiveness and productivity of federal research and development (R&D) efforts. The Committee will address significant national policy matters that cut across agency boundaries and shall provide a formal mechanism for interagency policy coordination and the development of federal technology activities. The Committee will act to improve the coordination of all federal efforts in technology. This includes creating balanced and comprehensive R&D programs, establishing structures to improve the way the federal government plans and coordinates R&D, and advising the Director, Office of Science and Technology Policy, and the Director, Office of Management and Budget, on R&D budget crosscuts and priorities.

8 The National Science and Technology Council (NSTC) was established by an Executive Order on November 23, 1993. This Cabinet-level Council is the principal means for the President of the United States to coordinate science, space, and technology to coordinate the diverse parts of the federal research and development enterprise. See, http://www.ostp.gov/NSTC/html/NSTC_Home.html.

9 Here, too, the NNI's recognition of nanotechnology's potential importance to the economy is clear.

10 Javanovic (1982) and Javanovic and Rousseau (2005) refer to the latter characteristic as ‘innovation spawning.’

11 David (1990) emphasizes that general purpose technology does not deliver productivity gains on arrival, hence our emphasis on expectations over time.

12 The 40 companies represent those for which the staff of the North Carolina Board of Science and Technology had a high degree of certainty regarding whether or not they were using nanotechnology. The staff constructed the list by searching the nanotechnology company directories of reputable organizations such as Small Times Media and NanoVIP.com; soliciting input from academic, corporate, and nonprofit researchers and staff in the state; conducting extensive Internet searches using a variety of relevant search terms; and drawing upon their first-hand knowledge of R&D and commercial activities in the state.

13 The Board is the state's leading government advisory body on issues related to science- and technology-based economic development. Established in 1963 by the state's legislature and currently housed in the state's Department of Commerce, its mission is to encourage, promote, and support scientific, engineering, and industrial research applications in North Carolina.

14 This data collection effort by the North Carolina Board of Science and Technology was also part of the state's overall Nanotechnology Initiative. See, http://www.ncscienceandtechnology.com.

15 Regarding the two companies that are not within the 30-mile radius shown in Figure 1, neither is within 30 miles of a university-based nanotechnology research center nor in another state.

16 Scholars have not yet formally tied the geographic nexus among nanotechnology companies and universities to cluster theory, but we believe that is only a matter of time because the pattern in Figure 1 is certainly not atypical.

17 For an in-depth discussion of technology-related market failure, see Link and Scott (2005) and Link (2006).

18 Data on company R&D expenditures, in total or as a ratio to a measure of size, were not available.

19 Size also allows for an indirect test of Gilbrat's Law. Gilbrat's Law states that the size of a company and its growth rate are independent, although the empirical evidence is mixed (Sutton, 1997). We hypothesize that it follows that the size of a company and its need for resources that generate growth are also independent.

20 When either employment (1000s) or revenues ($M) were reported on the survey as a range of values, the mid-point of the range was used.

21 These results are available upon request from the authors.

22 See Bozeman (2000) for a review of this literature.

23 In fact, there is uncertainly about the present size of the national population of US nanotechnology companies. One estimate places the total at 391. See, www.nanotech-now.com/business.htm. Another estimate is 860. See, www.nanovip.com/directory/International/index.php. Lux Research estimates the US population of nanotechnology companies at 1100. These differences are, in all likelihood, due to differences in the definition of nanotechnology.

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