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The Impact of Mission-Oriented Initiatives on University Research: The Case of Nanotechnology in the U.S.

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Abstract

We examine how the National Nanotechnology Initiative (NNI), a most recent U.S. government?s mission-oriented initiative launched in 2000, impacts the nature of university research in nanotechnology. We characterize the NNI as a policy intervention that targets the commercialization of technology and a focused research direction to promote national economic growth. As such, we expect that the NNI has brought about unintended consequences in terms of the direction of university-industry knowledge flows and the characteristics of university research output in nanotechnology. Using the difference-in-differences analysis of the U.S. nanotechnology patents filed between 1996 and 2007, we find that, for U.S. universities, the NNI has increased knowledge inflows from the industry, diminished the branching-out to novel technologies, reduced the research scope, and decreased the likelihood of technological breakthroughs, as compared to other U.S. and non-U.S. research institutions. Our findings suggest that, at least in the case of the NNI, mission-oriented government initiatives may exercise significant impacts on university research, but potentially in a less desirable way. Jelcodes:O38,O31

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ABSTRACT

We examine how the National Nanotechnology Initiative (NNI), a most recent U.S. government's mission-oriented initiative launched in 2000, impacts the nature of university research in nanotechnology. We characterize the NNI as a policy intervention that targets the commercialization of technology and a focused research direction to promote national economic growth. As such, we expect that the NNI has brought about unintended consequences in terms of the direction of university-industry knowledge flows and the characteristics of university research output in nanotechnology. Using the difference-in-differences analysis of the U.S. nanotechnology patents filed between 1996 and 2007, we find that, for U.S. universities, the NNI has increased knowledge inflows from the industry, diminished the branching-out to novel technologies, reduced the research scope, and decreased the likelihood of technological breakthroughs, as compared to other U.S. and non-U.S. research institutions. Our findings suggest that, at least in the case of the NNI, mission-oriented government initiatives may exercise significant impacts on university research, but potentially in a less desirable way.

INTRODUCTION

Since Vannevar Bush (1945) proposed in his influential report, *Science: The Endless Frontier*, the importance of basic research for advances in applied research followed by commercialization, government agencies have supported universities to maximize the payoffs from university research for the national economic growth. Policymakers have argued that a stronger government support would enhance the effectiveness of the national innovation system. Based on this logic, at least in the U.S., government agencies have become primary funding sources of university research (Nelson, 2004; Stephan, 2010). Behind the economic rationale for the governmental support of university research lies the concern about market failure that leads the private sector to underinvest in basic research due to the difficulty of appropriating from such investments (Arrow, 1962; Nelson, 1959; Dasgupta and David, 1994).

While national priorities play a role in setting broad research directions in Bush's manifesto, his original argument suggested a high degree of autonomy for science (Bush, 1945; Nelson, 2004; Mowery, 2009). Further, researchers have argued that decisions on specific areas to be funded should be left to scientists (Martin, 2003; Mowery, 2009). This casts a fundamental contrast with recent government research agenda that promote mission-oriented initiatives. Mowery's survey (2009) reported that most (over 90% in the U.S.) of the government research and development (R&D) spending is associated with mission-oriented research rationales. These initiatives may redirect university research to work on specific technology areas to maximize economic payoffs from the government funding (Dasgupta and David, 1994). In particular, the missions set up by the government may significantly affect the institutions of knowledge production and, hence, alter the landscape and flows of knowledge. We propose government mission-oriented initiatives as a condition in which the linear model a la Bush (1945) becomes limited in explaining how university research triggers and influences industrial R&D. By now it became apparent that the linear model, in its strongest form, lacks applicability (Cohen, Nelson, and Walsh, 2002) because a scientist can be simultaneously inspired by basic and applied research (Stokes, 1997) and new applied science is stimulated by both upstream science and downstream market needs (Rosenberg, 1974). We add to this line of literature by proposing and demonstrating that government initiatives in science and technology may complicate even the "adaptation" of the linear model. We submit that mission-oriented government initiatives may alter the characteristics of university research in technology development by influencing the direction of university research and by potentially overemphasizing the link to commercialization.

Despite the existing research on the influence of government funding on overall research outcomes, little is known as to how the initiatives of government agencies with specific missions may interfere with science and technology (Jaffe, 2006). Researchers have recently begun to respond to this knowledge gap by examining the role of institutions and science policy in knowledge accumulation and the direction of scientific research (Furman and Stern, 2010; Furman, Murray, and Stern, 2010). However, among what remains unexplored is the effect of government initiatives on knowledge flows and the nature of knowledge produced in the institutions such as universities that rely heavily on government funding. This omission is puzzling because government initiatives might be conflicting with the propositions that institutions of scientific research should be self-governed and thus independently decide the priority of their research agenda (Polanyi, 1962), and that the results of scientific research should be publicly disclosed and shared (Dasgupta and David, 1994; Nelson, 2004). To fill this gap, we address the following question: what is the effect of a particular technology initiative of the government on university research in terms of direction of knowledge flow between university and industry, exploration, research scope and technological breakthroughs.

We argue that the government initiative's emphasis on commercialization will induce university research to increasingly utilize knowledge flows from industry because firms tend to have technologies to resolve problems that are directly relevant to market demand; due to greater interests in economic returns, university researchers will reduce accessibility to their findings by secrecy and incomplete disclosures, which, in turn, foreclose their own possibility for branching-out to subsequent novel technology developments. We also contend that a focused research direction mandated by the government initiatives will cause university research to reduce exploring uncertain technologies and, thus, the variance of technological outcomes, leading to curtailed technological breakthroughs.

Our empirical setting is the National Nanotechnology Initiative (NNI), a U.S. federal government technology policy launched in 2000. Since its inception, the NNI has coordinated the disbursement of $14 billion by 2011. By allocating the NNI funding to nanotechnology R&D, federal agencies guide the direction of university research toward their mission-oriented agenda (Bush, 1945; Dasgupta and David, 1994; Mowery, 2009). Following Ergas (1987) and Mowery (2009), we characterize the NNI as a mission-oriented government initiative in that the NNI not only serves specific government missions in national defense, agriculture, health, and education, but also aims at securing the U.S. leadership in nanotechnology.[1] In particular, we view the NNI as the onset of a policy regime that emphasizes the commercialization of nanotechnology and a focused research direction to attain national economic growth. This initiative sets the university apart from the private sector that was largely unaffected by this policy drive. It also distinguishes the U.S. from

[1] The PCAST (The President's Committee of Advisors on Science and Technology) noted the NNI as having "an excellent multi-agency framework to ensure U.S. leadership in this emerging field that will be essential for economic and national security leadership in the first half of the next century" (NNI-The Initiative and Its Implementation Plan, 2000).

other countries that were free of such a policy shift during the period of study. Hence, the NNI provides a nice natural experiment that we can exploit to isolate the impact of this particular policy regime on university research outcomes.

Analyzing over 4,000 nanotechnology patents filed with the United States Patent and Trademark Office (USPTO) between 1996 and 2007, we find support for our general hypothesis. Specifically, our difference-in-differences estimations show that the NNI has 1) increased knowledge flows from industry to university; 2) lowered the propensity for universities to branch out to novel technology areas; 3) reduced the scope of university-generated patents; and 4) decreased the likelihood that the university research results in technological breakthroughs. These results are unexpected because the goals of mission-oriented government initiatives are in general to facilitate knowledge transfers from university to industry, not the reverse, and to build a strong national innovation system characterized by greater innovative output. Our findings thus suggest that mission-oriented government initiatives exert significant impacts on university research, but potentially in a less desirable way.

NNI AS A SCIENCE POLICY

The NNI is the U.S. federal government's interagency program for coordinating R&D and enhancing communication and collaborative activities in nanoscale science, engineering, and technology. The NNI represents the individual and cooperative nanotechnology-related activities of 25 federal agencies[2] with a range of research and regulatory roles and responsibilities. The primary goals of this initiative are to increase the transfer of new technologies from university to industry and facilitate the commercialization of

[2] Appendix 1 lists federal agencies participating in the NNI and their NNI-related budgets in 2010.

nanotechnology (NNI Strategic plan, 2011). Federal agencies put coordinated efforts toward identifying specific R&D targets and setting up R&D directions[3] in nanotechnology and expediting commercialization by focusing on applications (NNI-Research direction II, 2004).

Funding is the main mechanism that the NNI uses to achieve its goals by supporting nanotechnology research. The participating federal agencies have pre-allocated R&D budgets for nanotechnology; the reported NNI budget represents the collective sum of these agency-level budgets. Federal research grants are awarded by individual government agencies in accordance with their respective missions. While the NNI utilizes a traditional government funding system, it drives a national strategic plan for nanotechnology with integrated and unified directions across funding agencies. The NNI has been one of the top priorities in the science policy agenda that former Presidents have pursued. On January 21, 2000, President Clinton announced the launch of the NNI in a public address at the California Institute of Technology. On December 3, 2003, following up on the Clinton Administration's initiative, President Bush signed into law the "21st Century Nanotechnology Research and Development Act," which guaranteed a multi-year funding into nanotechnology research. To support the interests of these high-profile policy makers and respond to the calls by the Act, the NNI needed to make the benefit of the increased funding tangible and enforce the requirements of reviews and reporting (Lane and Kalil, 2005). The 2010 budget provides $1.9 billion for the NNI, reflecting a steady growth in the NNI investment (see Figure 1). The cumulative NNI investment since 2001, including the 2011 request, totals $14 billion. This magnitude of budget makes the NNI the biggest U.S. government science program since the

[3] An early-stage plan for the NNI included fairly specific guidelines. For instance, the deliverables in the first five years were to "…develop new standard reference materials for semiconductor, lab-on-a-chip-technologies, nanomagnetics, and calibration and quality assurance analysis for nanosystem first achieved by FY2003… [and to] develop 3-D measurement methods for the analysis for physical and chemical at or near atomic spatial resolution first achieved by FY2004 …" (NNI – The Initiatives and Implementations Plan, 2000).

Apollo Program initiated in 1961 under the Kennedy Administration.

The NNI program involves many actors such as universities, government, and industry. From the beginning, the NNI has hosted a series of workshops inviting these actors to identify major technological barriers to achieving its goal, which is to promote the economic competitiveness of the U.S.[4] These workshops play a significant role in highlighting the need for targeted funding and in setting up focused research directions by gathering inputs from and informing strategic plans to the scientific community. In particular, these workshops underscore specific research targets and metrics of progress toward those targets and the commercialization efforts for economic growth. For instance, a report from one of these workshop sessions shows the participants' strong interests in licensing, intellectual property rights, and new business models in nanotechnology (NNI-Southern Regional Workshop, 2002).

This practical orientation of the NNI may exert disproportionally greater impacts on university research than on the R&D in other institutions because the direction of NNI-led investments for economic returns presents a starker contrast with what the university research purports to advance. Further, more important for our empirical design, the emphasis on focused research and commercialization appears largely exogenous to the academic community. Note that the norm of university research has always been the "communism" and the "disinterestedness" (Merton, 1973). Though some prominent university scholars provided individual inputs to the NNI's establishment[5], the academic community on the whole seems

[4] Since 2000, the Nanoscale Science, Engineering, and Technology Committee, the subcommittee of the National Science and Technology Council, has organized over 20 official NNI workshops and, separately, the NNI participating agencies have organized many more workshops that were affiliated with or supportive of the initiative (NNI-Strategic Planning Stakeholder Workshop, 2010).

[5] The inputs from these prominent scholars have been general endorsements to nanotechnology as a promising field that deserves aggressive national investment, rather than suggestions of specific research topics to be included in the agenda. For instance, Richard Smalley, a Nobel Laureate in chemistry, concluded in his testimony to the Senate Subcommittee on Science, Technology, and Space: "We are about to be able to build

to have been largely disinterested in the specifics of the initiatives and, hence, the agenda of the NNI can be considered as exogenous to the academic community.[6]

The U.S. NNI is probably one of the strongest mission-oriented government initiatives we know of in early 21st century. Other countries such as Japan, U.K., Germany, and France that are known for their high nanotechnology capabilities did not show a noticeable shift in their nanotechnology policies until 2010, when U.K.[7] and Germany[8] finally introduced national nanotechnology policies similar to the NNI. Japan and France have traditionally focused on industry nanotechnology research and their science policies for nanotechnology remained unchanged since late 1980s.[9] We found no evidence of significant shifts in science policy regime for nanotechnology in these advanced countries during the period of our study. Thus, these countries seem to be free of any government mission initiatives that might have directly affected university nanotechnology research in a similar way that the NNI did to the U.S. universities. Therefore, we consider the NNI as a policy intervention that constitutes a reasonable natural experiment by which we can identify the impact of a mission-oriented government initiative on university research, relative to the research conducted in other U.S. and non-U.S. institutions.

THEORY AND HYPOTHESIS

NNI and Knowledge Flows

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things that work on the smallest possible length scales. It is in our Nation's best interest to move boldly into this new field." (Nanotechnology Research Directions: IWGN Workshop Report, 1999).

[6] Our interviews with scientists confirm this point that they were not aware of or interested in the NNI agenda until they were presented with the related funding opportunity announcement.

[7] UK, Nanotechnology Strategy: Small Technologies, Great Opportunity. March 2010. http://webarchive.nationalarchives.gov.uk/+/interactive.bis.gov.uk/nano/. Accessed on December 4, 2011.

[8] Germany, Nano Initiative – Action Plan 2010. http://www.research-in-germany.de/dachportal/en/v-links-and-downloads-einordnen/downloads/nano/2176/nanobroschuere.pdf. Accessed on December 4, 2011.

[9] For instance, France has developed its nanotechnology based on geographical industry clusters as a network of micro-nano platforms since 1970 (MAIT, 2009). Japan has driven governmental support to establish a new industry of nanotechnology by building industry consortium such as Semiconductor Industry Research Institute Japan (Present Status of Japanese Nanotechnology Efforts, 1997).

To the extent that nanotechnology research in university relies on NNI funding, university researchers should be responsive to the government initiatives and thus may accordingly align their research with those strategic goals to ensure continued funding. For several reasons, we consider this assumption as reasonable. First, the federal government has been the largest sponsor of university research, providing over 60% of the research budget (Stephan, 2010). Second, funding agencies have influenced the focus of university research by setting up specific goals (Bush, 1945; Nelson, 2004; Vallas and Kleinman, 2008; Mowery, 2009). Third, university nanotechnology researchers compete for NNI-funded grants (Lane and Kalil, 2005). We do not mean that university researchers necessarily change their research direction as radically as from basic research to applied research (Thursby and Thursby, 2003). Rather, we expect that, to qualify for funding, university researchers will have to pay attention to the NNI agenda in determining their research direction[10] and hence, at the margin, the research outcome will bear out the impact of these initiatives to a measurable extent.

Recall that the NNI focuses on facilitating the application of nanotechnology. One of the NNI's purported strategic goals is to foster the conversion of new technologies into products for commercial and public benefits (cf. Mowery, 2009). Because solving practical problems often leads to important basic research findings as byproducts, university researchers may be willing to adopt the NNI research agenda that have practical orientations. This motivates the university researchers to pay increased attention to technological developments from the industry (Rosenberg, 1990; Stokes, 1997). That is, when mission-oriented initiatives are in place, the university research that inherently seeks no immediate

[10] For example, when university researchers find a funding program broadly fitting to their research directions, they may adjust the details of their research to meet the specific requirements of that program.

practical application and yet involves greater motives of utility may take the development in the industry as a reference point. This is because the industry is another important institution that possesses knowledge about the current state of technology and the opportunities for improvement (Nelson and Winter, 1982). To meet the funding agencies' initiatives, universities may seek technological inputs from the industry that applies nanotechnology primarily to commercial ends. The industry-generated technology might have information that is fundamentally different from the university-generated technology because downstream technologies tend to be developed in response to market demands (Von Hippel, 1988; Cohen, Nelson and Walsh, 2002). The input from the industry can thus be useful for understanding the practical application of the technology. Therefore, under the NNI, university researchers will have greater motivations to appropriate from the technological developments in the industry. The form of this appropriation would, however, not be limited to simply obtaining practical ideas from the industry. University researchers can use any areas of research in which the industry possesses relatively advanced technology such as methods, tools, and new materials that are essential for solving problems and thereby producing outcomes with implications for practical use.[11] Hence, with the launch of the NNI, university researchers may have looked to the industry technology significantly more than they did before. This has likely resulted in an increase of knowledge flows from the industry to the university. Hence, we hypothesize the following:

Hypothesis 1: The NNI has likely increased knowledge flows from the industry to the U.S. university in nanotechnology.

[11] For instance, the Atomic Force Microscopy (AFM) or the Scanning Tunneling Microscopy (STM), which enables researchers to image, measure, and manipulate matter at the nanoscale, was first developed by a group of IBM scientists in 1981. Since then, a significant body of university research has relied on this particular technology to develop the next level of technology. The discovery of nanotubes exhibits a similar case. Since the NEC's discovery of multi-walled carbon nanotubes in 1991, nanotubes have become an important topic in university nanotechnology research.

NNI and Branching-Out to Novel Technology Areas

The mission-oriented agenda for facilitating the application and commercialization of technology may have accelerated the privatization of university research outcomes. The privatization of research results is essentially an induced effect by the NNI that emphasizes the connection of its sponsored research to economic activities. For instance, under the NNI, universities are encouraged to file patents on research results or take additional steps toward commercialization such as licensing materials, founding companies, and cooperating with industrial material suppliers or manufacturers.[12] [13] In response to the emphasis in economic values of nanotechnology research, the concern of property rights has likely increased among university researchers who would be otherwise disinterested in pursuing property rights, thereby leading to the increased privatization of their research findings (Demsetz, 1967).

When a certain technology is privatized in early stages of development, the successive generation of diverse and useful derivative ideas may be hindered by the restricted access to prior technology (Dasgupta and David, 1994; Nelson, 2004; Aghion, Dewatripont, and Stein, 2008). As knowledge is accumulated over time, prior knowledge becomes a critical input for new knowledge generation (Fleming, 2001). Imagine the path for technology development as randomly dispersed branching-outs from prior nodes of technology to the next nodes of new technology. These branching-outs occur in a process where the components of accumulated knowledge are recombined to produce an invention. Thus, the

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[12] Some excerpts from NNI documents include related contents. For example, "…nanotechnology research… , which will drive the creation of new intellectual property and wealth generation through new companies in medical applications…" (The NNI workshop, 2002). According to the 21st Century Nanotechnology R&D Act, the NNI shall establish metrics for evaluation. Prior studies that examine the nanotechnology development use patent data as a direct measure of technological innovation (Roco, 2007, 2011).

[13] The NNI official website describes nanotechnology achievements, many of which include the part of "Patent and other steps toward commercialization" (See Appendix 2 for an example). This implies that the NNI considers patenting as a step toward commercialization. http://www.nano.gov/nanotechnology-initiatives/nano-achievements. Accessed on December 4, 2011.
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access to prior knowledge is necessary for branching out to a new technology. If, for any reason, the access to certain prior technology is restricted, this prior technology cannot be used as an input for future technology developments and, hence, the subsequent branching-out from the technology is discouraged.

We argue that the NNI has restricted the access to prior knowledge generated by university research in nanotechnology and, thus, has decreased the branching-out to a new technology. There are two reasons for this expectation: increased secrecy and incomplete disclosure of research findings. First, with the NNI's commercialization orientation, the privatization of university research may have accompanied increased secrecy. To maximize the economic value of their research that can be potentially commercialized, university researchers may attempt to protect their findings with secrecy and refrain from making them freely available for future research (Walsh and Hong, 2003; Walsh , Cho and Cohen, 2005; Walsh et al., 2007).[14] University research has been an important open resource for future technology developments. When information sharing of research becomes problematic, the beneficiaries of this open source face restricted accessibility. The NNI's encouragement of patent filing of university research may mitigate the concern for the expropriation risk. However, patenting is generally a step toward commercialization (NNI Achievement[15]; Roco, 2011). Intellectual property rights such as patents per se do not restrict accessibility to the technology, but commercialization prompted by patenting can indeed reduce accessibility (Walsh et al., 2005, 2007). When university researchers consider or are involved in commercializing their research, they may increase secrecy to secure at least part of their research that is critical for commercialization. This is particularly so given that most licensed

[14] For instance, university researchers may become less willing to discuss research in progress with those outside the research group (Walsh and Hong, 2003).
[15] http://www.nano.gov/nanotechnology-initiatives/nano-achievements. Accessed on December 4, 2011.

university technologies are usually in embryonic stages and, hence, their commercialization requires further inputs from university researchers (Jensen and Thursby, 2001). While the increased secrecy reduces the expropriation risk of university research, it hides some research findings from the possible branching-out map of future technology development.

Second, the commercialization-oriented NNI initiatives may have triggered delays in disclosing, or partial disclosures of, university research findings. This slows down the accumulation of prior technologies that otherwise readily become inputs to new recombination. Commercialization activities such as licensing restrict, or at least delay, the disclosure of university research (Thursby and Thursby, 2002, 2003). The NNI as a federal funding mechanism per se does not reduce disclosures because the funding requires the research results to be disclosed eventually as achievements. However, since the NNI emphasizes explicit links to industry and commercialization, university researchers may conceal certain part of information from publishing, delay disclosures, or deny other researchers' request to share the research apparatus or intermediate research procedures (Dasgupta and David, 1994; Thursby and Thursby, 2003). The delay or incomplete disclosure may prevent some important findings, which could otherwise be a stepping stone for new technology developments, from appearing on future technology paths. Thus, delays in disclosure or partial disclosures reduce the supply of research findings. Consequently, the accessibility to prior university-generated knowledge becomes restricted.

The reduced accessibility to university research results will likely lead to fewer branching-outs to new technologies. This adverse effect is particularly to be greater for university researchers because open communication has been the norm in academia. It must be quite disturbing for university researchers that the access to peers' research findings is hindered, or peer researchers delay disclosures. Note that the reward system in academia traditionally depends only on priority (Merton, 1973). There is an inherent tension between full disclosure (to contribute to the accumulation of knowledge) and individual incentives (to win the priority race by reserving some parts of findings for own next research). Nevertheless, university researchers have learned that research is an infinitely repeated game and hence disclosing their findings is a dominant strategy (Dasgupta and David, 1994). The encouraged commercialization of university research distorts this reward system and the incentives of university researchers to disclose knowledge by adding another way to earn benefits. As a result, university researchers will choose to restrict the access of peer researchers if the expected economic rents are greater than the expected rents by disclosing their findings. Therefore, while the restricted accessibility to prior technology affects the whole research community that draws on university research as an open source for future developments, it impacts university research more significantly, leading to fewer branching-outs to new technology from university research. To summarize:

Hypothesis 2: The NNI has likely decreased the branching-out to new technology in the U.S. university research in nanotechnology.

NNI and Research Scope

Mission-oriented government initiatives set up the direction of research to align national research efforts to achieve the mission efficiently. For instance, the NNI plans to introduce prototypes, new products, and productive processes according to pre-defined timelines. Through its strategic plan reports, the NNI designates specific agenda for federal agencies and prescribes directions of nanotechnology research following extensive planning sessions (NNI-Research Directions II, 2004; Roco, 2011). Hence, for continued funding, university researchers need to show their “fit” with these directions and generate tangible outcomes in line with the initiatives. Mission-oriented research agenda and planning tend to improve overall performance of technology research (Lane and Kalil, 2005; Roco, 2007; Supplement to the President’s FY 2011 Budget, 2010). However, these guidelines may drive university researchers to focus on areas in which visible outcomes are anticipated along the pre-defined directions. While mission-oriented planning and management of technology might help increase research output in the designated research areas, it may narrow down the scope of university research by redirecting diverse research efforts toward specific areas of focus.

From the university researchers' standpoint, narrower research scopes may be preferable because broader scopes increase the complexity in recombining technological components across areas. Complexity tends to increase the uncertainty in outcomes because the number of unpredictable interactions between components is amplified (Fleming and Sorenson, 2004). Thus, university researchers are likely to avoid uncertainty by reducing the complexity, which will lead to a decreased research scope for each project. The following hypothesis summarizes the discussion:

Hypothesis 3: The NNI has likely decreased the research scope of the U.S. university research in nanotechnology.

NNI and Breakthrough Outcomes

A complete ex-ante prediction for scientific discovery or technology development is virtually impossible. Thus, the planning and management of research directions by government initiatives are liable to ignore or foreclose opportunities that could lead to breakthroughs in university research. Further, due to incomplete information and bounded rationality, even with carefully designed research programs there always remain unconsidered technological paths, some of which would have delivered significant breakthroughs.

Achieving breakthrough outcomes may also become harder because, under the mission-oriented initiatives such as the NNI, university researchers are likely to reduce exploration. Following the argument in Hypothesis 3, the narrowed research scopes imply that university researchers exploit more the focused areas in which expected results are less uncertain but explore less frequently in areas with greater uncertainty in outcomes. Fewer branching-outs to novel technologies, as argued in Hypothesis 2, also suggest that university researchers reduce exploration. To branch out to a new technology, university researchers need to take the risk of challenging uncertain paths, search across various technological components, and try out untapped recombination of existing technologies. Narrowed research scope and fewer branching-outs would reflect the reduction in these types of activities. Decreased explorations in university research will lead to smaller variances and, more importantly, fewer outliers in research performance (March, 1991). Reductions in both tails in the performance distribution imply less frequent breakthroughs (March 1991; Singh and Fleming, 2010) as well as fewer failures. Therefore, with the NNI, university researchers are likely to have reduced exploration and thus produced fewer breakthrough outcomes.

We have so far argued that university researchers reduce exploration *outside* the paths designated by mission-oriented initiatives. However, because mission-oriented initiatives may encourage university researchers to explore *within* the pre-defined paths, we need to consider if this type of exploration could contribute to technological breakthroughs. Within a pre-defined path, searches and variations may be only short-lived because the technological sources that can be combined into a new technology are much more limited than in areas outside the path. The force that drives university nanotechnology research into areas of promising results may improve the efficiency and hence increase the mean value of outcomes or reduce failures, but it cannot increase the portion of breakthrough outcomes. Taken together, under the NNI that pursues the pre-defined paths for technological development, university researchers are likely to focus their exploration within the paths with less uncertainty, thereby generating fewer breakthrough outliers. Hence, we hypothesize the following:

Hypothesis 4: The NNI has likely decreased the proportion of technological breakthroughs from the U.S. university research in nanotechnology.

EMPIRICAL DESIGN

To test our hypotheses, it is not enough to simply demonstrate differences in the characteristics of the U.S. university research before and after the launch of the NNI because the differences may be confounded by various factors that may be at play along the lifecycle of nanotechnology. Hence, we care to address an important specification issue, i.e., the counterfactual. If the NNI changed the nature of university research, the difference between the pre- and post-NNI university research in the U.S. would become clear only when compared with other U.S. and non-U.S. institutions that conducted nanotechnology research but were immune to, or at least less influenced by, the NNI. Thus, we employ the difference-in-differences estimation to isolate the marginal effect of the NNI on the U.S. university research from the influences of generic factors in the development of nanotechnology.

For empirical specifications, we exploit two elements. First, other U.S. and non-U.S. institutions and organizations also perform nanotechnology research. Thus, we first identify the type (university, industry, and other research institutions) and the nationality (U.S., U.K., Germany, Japan, and France) of nanotechnology research institutions. We chose these four non-U.S. countries because they have the largest number of U.S. nanotechnology patents[16] but experienced no significant changes in their science policy for nanotechnology, at least not during the period of our study. As argued earlier, the NNI has likely exerted the greatest impact on university research because it asked university researchers to perform what they have been largely unfamiliar with, i.e., focused research and the commercialization of research outcomes. In contrast, other research institutions, particularly the industry, may have been affected much less by the NNI's emphasis on the economic benefit and targeted research because these are essentially what they have been doing routinely. For the analysis,

[16] Together, they claim over 70% of all nanotechnology patents filed by non-U.S. organizations during the period of study.

we divide the patents into a “treatment” group (nanotechnology patents by the U.S. universities) and a “control” group (nanotechnology patents by all other institutions). As a robust check, we vary control groups by non-U.S. universities or the U.S. non-universities.

Second, the NNI began in 2000, which is long after the enactment of the Bayh Dole Act of 1980. Hence, by the NNI launch, any impact of this legislation on university research has presumably been stabilized. Thus, we consider the impact of the NNI to be orthogonal to the overall tendency toward commercialization of university research prompted by the Bayh Dole Act. Moreover, while the university research community as a whole seems to have been unaware of the launch or specific goals of the NNI, university researchers learn the direction of the initiatives when they find the Funding Opportunities Announcement from the NNI federal agencies. According to its strategic plan, the NNI seeks to achieve the goals by influencing each participating agency’s funding opportunities that attract the interest of university researchers. Therefore, the NNI is reasonably exogenous to university research and our difference-in-differences analysis exploits this property.

We construct our dataset using a public trail of nanotechnology research, i.e., nanotechnology patents filed with and granted by the USPTO. At least for three reasons, nanotechnology patent data are suitable for our empirical corroboration. First, patent data provide unique contents including application dates and technology subclasses. Because each patent lists the application date that is close to the time of research, they can provide a basis for systematically measuring the impact of the NNI. Moreover, patent data provide the subclass-level technology classification. The three-digit nanotechnology class 977 covers a collection of 264 distinct subclass references. Subclasses are very useful for capturing technological changes because they provide fine-grained information for technology development (Trajtenberg, Henderson, and Jaffe, 1997; Thompson and Fox-Kean, 2005).

Second, patent citations reflect knowledge flows, though not perfectly (Jaffe, Trajtenberg, Henderson, 1993; Mowery, Oxley, and Silverman, 1996; Gomes-Casseres, Hagedoorn, and Jaffe, 2006). There is a concern that patent citations might be a noisy proxy for knowledge flows due to, for instance, examiner-added citations (Alacer and Gittelman, 2006). Nevertheless, we draw on a recent study demonstrating that citations and knowledge flows are highly correlated in the aggregate level (Jaffe, Trajtenberg, and Fogarty, 2005). The finding suggests that "aggregate" citations can be used as good proxies for knowledge flows between organizations. Our comparison is conducted at the organization level (U.S. universities vs. other institutions), which justifies the use of patent citations as a meaningful proxy for interorganizational knowledge flows. Moreover, the empirical setting of our study further mitigates the concern because nanotechnology has characteristics of not only an emerging field but also a "Grilichesian breakthrough—creating technological opportunities across a range of fields" (Darby and Zucker, 2003; Sampat, 2004). This means that examiners face greater challenges in searching prior art due to inexperience and a broader distribution of nanotechnology across different fields and, hence, add fewer citations compared to other technology fields (Sampat, 2004). Indeed, Sampat (2004) shows that examiner-added citations in nanotechnology (20%) are significantly lower than the average (28%).

Third, there is a well-established tradition in the patent literature of measuring technological breakthroughs by forward citations (e.g., Singh and Fleming, 2010). The intensity of forward citations represents not only a technological significance but also the economic value of a technology such as consumer surplus generated (Trajtenberg, 1990) or the organization's market value (Hall, Jaffe, and Trajtenberg, 2005). This well fits the NNI's goal, which is to improve the economic value of technology. Hence, we can effectively use forward citations to measure the NNI effect on the production of technological breakthroughs from university research.

Data

We identified 5,401 nanotechnology patents filed by the institutions in the U.S., U.K., Japan, Germany, and France from 1970 to 2010, using the USPTO-entitled patents assigned to the Class 977 (Nanotechnology).[17] We downloaded the data from the USPTO website and parsed them, matching patent assignees with organization identifier from Nanobank (Zucker et al., 2007). Since the U.S. patents or pre-grant publications can be classified into 977 only as cross-references or secondary classifications (USPTO Classification order 1850, 2005), the Class 977 helps us to identify all patented nanotechnology research across all scientific fields (e.g., physics, chemistry, material science, and biology).

Our data construction also identified: (1) nanotechnology patents that are cited by any of these 5,401 nanotechnology patents (backward citations); (2) 11,095 subclass pairs under Class 977; and (3) the number of citations made by 2010 to these nanotechnology patents (forward citations). For the analysis, we use the five-year window surrounding the year 2002 (i.e., 1997-2001 and 2002-2006) to compare between the pre- and post-NNI.[18]

Dependent Variables

We utilized four measures of outcomes to test our hypotheses on the impact of the NNI on university research.

Knowledge Flows from Industry We used backward citations to measure knowledge flows (Mowery, Oxley, and Silverman, 1996; Gomes-Casseres, Hagedoorn, and Jaffe, 2006). Specifically, we constructed the measure for each patent that is the number of backward citations made to industry nanotechnology patents divided by the number of backward citations made to all nanotechnology patents. Hence, this measure ranges from zero to one. Notice that the measure is undefined and hence was treated as missing for patents that

[17] In 2005, the USPTO established a new classification reference 977 for nanotechnology and re-classified all relevant patents into this class dating back to 1970.
[18] We also used four- and six-year windows for robustness checks. We obtained very similar results from these variations.

do not cite prior nanotechnology patents. There were 3,091 nanotechnology patents that had at least one backward citation to prior nanotechnology patents.

Branching-Out to Novel Technology Because subclasses allow us to examine fine-grained classifications of nanotechnology (Trajtenberg, Henderson, and Jaffe, 1997; Thompson and Fox-Kean, 2005), researchers increasingly focus on the subclass classification of patents to examine technology transfer, technology recombination, and patent scope (Lerner, 1994; Fleming, 2001; Thompson and Fox-Kean, 2005; Fleming and Sorenson, 2004; Fleming, Mingo, and Chen, 2007). A first-ever recombination of two subclasses can be considered as inventing a new aspect of corresponding technology (Fleming, 2001; Fleming and Sorenson, 2004; Fleming, Mingo, and Chen, 2007). Following this convention, we measured the branching-out to a new technology by the new recombination of subclasses that a nanotechnology patent establishes for the first time within the Class 977. For each nanotechnology patent, we constructed a dummy variable that indicates if the patent incorporates a branching-out.

Research Scope Subclasses were developed recently to address the shortcomings associated with defining a technology by single aspect (Handbook of Classification, 2005). Thus, subclass classifications convey additional information about the technology within the three-digit class technology. We measured the research scope of nanotechnology by the number of subclasses within the Class 977.[19] Notice that we consider each patent as the unit of research and, hence, treat the patent scope as equivalent to the research scope. If a nanotechnology patent covers broader scopes of research in nanotechnology, it would be classified to more subclasses within the Class 977. Hence, all

[19] One might alternatively use the number of International Patent Classification (IPC) classes to proxy for patent scope (e.g., Lerner, 1994). However, IPC classes are intended for industry and profession (Lerner, 1994), whereas the U.S. subclass classification scheme is based on the structure and function of technology. Given the interest of our study in the change of technological nature, subclass classifications appear more appropriate.

else equal, a greater number of subclasses imply a broader scope of research underlying the patent.

Technological Breakthroughs The patent literature has established forward citations as an indicator of economic, social, and technological success of the patented technology (e.g., Singh and Fleming, 2010). Following this convention, we measure technological breakthroughs using forward citations. Specifically, we first generated the citation distribution of the entire population of U.S. patents (about 3.9 million) granted during 1976-2010. To account for differences in the citation hazard due to timing and technology, we regressed the number of forward citations on patent class, application year, and grant year to recover the residuals. This adjustment allows us to compare the number of forward citations across patents that were applied for and granted in the same year and in the same technology class. We then computed the z-scores based on these normalized forward citations. Finally, we defined a technological breakthrough as the patent belonging to the top 5% of the citation distribution (Singh and Fleming, 2010) and assigned '1' to the measure for these patents and '0' for others.

Independent Variables

The independent variables for the main models are the indicators of the post-NNI period and the U.S. university. The indicator of the post-NNI period, *PostNNI*, signifies whether the patent was filed in or after 2002. We defined *PostNNI* to cover the period from one year after 2001, considering that patents can be applied for only after some research results are achieved. Because the NNI was announced in early 2000 and the actual funding grew significantly in 2001 (see Figure2), it seems reasonable to allow for at least one year of time lag for the NNI to take into measurable effect. The U.S. university indicator, *USuniversity*, represents whether the assignee of the patent is a U.S. university. For the patents that are co-assigned to university and other institutions, we classified them as university patents.[20] We use the interaction term between *PostNNI* and *USuniversity* to single out the hypothesized effects of the NNI on university research.

Control Variables

Non-patent References The technology associated with each patent has a different degree of basicness or commercialization potential. A more basic or less applied technology may, by nature, be associated with less knowledge flows from the industry and/or receive more citations. Hence, we controlled for this effect by including the number of *non-patent references* in the tests for Hypotheses 1 and 4. We expect that *non-patent references* capture another confounding effect of academic knowledge on future citations. This proxy for the usage of academic knowledge is also highly correlated with citation measures (Fleming and Sorenson, 2004; Ahuja and Katila, 2004). Hence, *non-patent references* controls for the effect of academic knowledge on citation measures that we use to examine knowledge flows (Hypothesis 1) and technological breakthroughs (Hypothesis 4).[21]

Claims We included the number of claims to control for the effect of patent claims on the dependent variables. In particular, we expect that patents with more claims are likely to command more forward citations, more subclass references, and fewer backward citations to industry patents. Patent claims reflect the technological originality or the coverage of protection and, hence, may be positively correlated with the novelty, scope, and usefulness of technology. On the other hand, patent claims may be negatively correlated with backward citations to industry patents because the reliance on prior art reduces room for

[20] Classifying these patens as non-university patents makes little changes to the results.

[21] Because we expect that non-patent references are theoretically orthogonal to the dependent variables that are based on subclasses, the main models testing Hypothesis 2 and 3 do not include this variable as control. Controlling for non-patent references makes little changes to the results.

novel claims.

Univeristy-Firm Co-patent We included the dummy for patents that are co-assigned to university and firm to control for the effect of firm-involved university research.

Year Effects We included the application year dummies to capture the temporal effects in the development of nanotechnology.

Table 1 provides summary statistics of these variables and the correlations between them. No pair of explanatory variables exhibits a correlation that is high enough to cause any concern of multicollinearity.

Insert Table 1about here

Estimation Method

For Hypothesis 1, we operationalize the dependent variable as the share of backward citations made to industry patents. Hence, we begin with an OLS specification. As a robustness check, we also estimate the negative binomial model with the number of backward citations as the dependent variable. For Hypotheses 2 and 4, we estimate logit models with the dependent variable indicating whether each patent branched out to novel recombination (H2) or belonged to the top 5% in the citation distribution (H4). For Hypothesis 4, we alternatively use an OLS estimation that operationalizes the dependent variable as the standard normalized forward citations. For Hypothesis 3, we use a log-log linear model and a negative binomial model. In all models, we report heteroskedasticity-robust standard errors.

Our main empirical model is the following:

$$\text{Dependent Variables} = f\left(\varepsilon_i;\ \alpha_t + \beta_1 PostNNI + \beta_2 US\ university + \beta_3 PostNNI * US\ university\right)$$

where α_t is the year effect, β_i's are the coefficients to be estimated, and ε_t is the error term. Table 2 reports the estimation results. For robustness tests, we estimate the following models:

$$\text{Dependent Variable} = f\left(\varepsilon_i;\ \alpha_t + \beta_1 PostNNI + \beta_2 US\ + \beta_3 PostNNI * US\right)$$

on the university-only sample that consists of the U.S. and non-U.S. universities, and,

$$\text{Dependent Variables} = f(\varepsilon_i;\ \alpha_t + \beta_1 PostNNI + \beta_2 University + \beta_3 PostNNI * University)$$

on the U.S. only sample. We test on the latter sample to obtain the most conservative estimates. That is because U.S. institutions may be going through the same life-cycle of nanotechnology and, hence, by restricting to this subsample we can address the concern for a confounding effect from differences in the technology life-cycle between countries. Table 3 presents the results of these additional estimations.

RESULTS

Previews

Figures 3, 5, 7 and 9 illustrate knowledge flows from industry, branching-out to new technology, research scope, and technological breakthroughs, respectively, of the research in the U.S. universities as compared to that in all other institutions from 1990 to 2006. Overall, these figures appear quite noisy and do not show clear trends due to large year-to-year fluctuations. However, dividing the period of study into two five-year windows (i.e., pre-NNI and post-NNI) consistently reveals the significant marginal effect of the NNI on university research as compared to other institutions (Figures 4, 6, 8, 10, and 11). For each five-year window (i.e., 1997-2001 and 2002-2006), we compute and compare the mean values of the dependent variables for the U.S. university and all other institutions.

Insert Figure 1-11 about here

Figure 3 indicates that there are two peaks, in 1993 and 2001, of knowledge flows from the industry to the U.S. universities. The first peak represents heavy citations to the nanoscale measurement technology such as the AFM and the STM that the industry developed in early 1980s. However, the second boost in knowledge flows from the industry is likely caused by the NNI as we hypothesize. Figure 4 indicates that the NNI did not bring an absolute increase in the share of knowledge flows from the industry. However, the difference between the slopes implies that, when de-trended, the U.S. universities increased knowledge inflows from the industry after the NNI, more than other institutions did. Figure 5 indicates that the gap between the U.S. universities and other institutions in branching out to novel technologies is greater in the pre-NNI period than in the post-NNI period. Figure 6 clarifies such a difference between two periods. In terms of research scope, the difference seems less obvious in Figure 7, but the contrast becomes apparent in Figure 8; the research scope of U.S. universities declines more rapidly than that of other institutions between the periods. Figure 9 shows an overall decreasing trend in the proportion of breakthroughs in nanotechnology. However, Figure 10 suggests that the NNI may have accelerated the decrease in breakthrough output from the U.S. universities. Figure 11 strongly supports this interpretation by showing that the U.S. university research in the post-NNI period exhibits a decreased density for the right-tail outcomes. Interestingly, after the NNI, the mean value of the U.S. university research has increased but apparently at the expense of extreme outcomes in both tails.

Regression Results

Now we present the regression results. Models 2-1 (OLS) and 2-2 (negative binomial) in Table 2 support Hypothesis 1: the interaction term between the U.S. universities and the post-NNI indicated a positive and significant effect of the NNI on knowledge flows from the industry to the U.S. university.

Insert Table 2 and 3 about here

We found support to Hypothesis 2 from Models 2-3 and 2-4. In Model 2-3, the interaction term between the U.S. universities and the post-NNI indicated a negative and significant effect of the NNI on the U.S. university's branching-out to novel technologies. We also carefully considered a possibility that, by restricting the access to university research, the NNI may have adversely affected the entire U.S. nanotechnology research community including the industry. Thus, in Model 2-4, we ran a logit model with the U.S. indicator, *US*, and its interaction with *PostNNI*. This is to see if the U.S. nanotechnology research exhibits a distinct characteristic as compared to non-U.S. countries. The coefficient on the interaction term was significantly negative, indicating that, after the NNI, the U.S. institutions as a whole generated fewer branching-outs to novel technology relative to non-U.S. institutions.

Models 2-5 (OLS) and 2-6 (negative binomial) in Table 2 support Hypothesis 3: the interaction between the U.S. universities and the post-NNI indicated a negative and significant effect of the NNI on the research scope. That is, the research scope of the U.S. universities in nanotechnology has decreased following the launch of the NNI when compared to other U.S. and non-U.S. institutions.

Hypothesis 4 was also supported in Models 2-7 (logit) and 2-8 (OLS). In both models, the interaction term between the U.S. universities and the post-NNI indicated a negative and significant effect of the NNI on breakthrough outcomes. The analysis on subsets of the sample, in which the observations were divided into two groups—the above-mean outcome group ($Z\_norm > 0$) and the below-mean outcome group ($Z\_norm < 0$)—revealed that the NNI has decreased "successful" outcomes of the U.S. universityresearch in the post-NNI period relative to other institutions (Model 2-9), but not the "poor" outcomes thereof (Model 2-10).

To facilitate the interpretation of estimates, we calculated the magnitude of changes in the dependent variables after the NNI launch. For U.S. universities, knowledge inflows from firms increased by 36.1% and research scopes decreased by 10.2% in the post-NNI period. Moreover, the predicted odds of branching out to a new technology declined by 29.8% and the predicted odds of the technological breakthroughs decreased by a whopping 48.7% after the launch of the NNI.

We obtained robust results on subsets of data: the university-only sample and the

U.S.-only sample (Table 3). Model 3-1 and 3-2 together confirm that the NNI has increased knowledge flows from the industry to U.S. universities. The U.S. universities also reduced the branching-out to novel technologies in the post-NNI period but the reduction was not statistically significant when compared to non-U.S. universities (Model 3-3) or other U.S. institutions (Model 3-4). These results suggest that, while the U.S universities and U.S. research community as a whole reduced the branching-out in the post-NNI period, the U.S. universities and other U.S. institutions are indistinguishable from each other in that effect. Model 3-5 shows that the NNI in fact had greater adverse effects on the U.S. industry's branching-out relative to the industry in other countries. The result of Model 2-5 and 2-6 about research scope was confirmed on the university-only sample (Model 3-6) and the U.S.-only sample (Model 3-7). These models support that the NNI has decreased the research scope of the U.S. universities relative to all other institutions. Finally, results on the U.S.-only sample (Models 3-8 and 3-10) and the university-only sample (Model 3-9) provide confirmatory evidence that the NNI has reduced technological breakthroughs generated by the U.S. universities.

Robustness Checks

We performed the same analysis with varying time windows for the NNI regime. First, we dropped observations for 2001 because, being a transition period, the year 2001 could represent a turbulent environment characterized by strong initial policy drives and the phenomenal increase in funding (see Figure 2). Thus, we modified the five-year windows (i.e., 1996-2000 and 2002-2006) and re-estimated the entire models. The results were robust to this variation (unreported). Second, we employed four- and six-year windows surrounding 2001 and re-estimated our preferred models for each hypothesis. The results, reported in Models (4-1) through (4-8) in Table 4, were generally robust except that the four-year window-based test of Hypothesis 2 (Model 4-2) lacked significance, though the sign was consistent with the prediction.

Insert Table 4 about here

DISCUSSION AND CONCLUSION

The purpose of this paper is to examine the impact of a specific mission-oriented government initiative, namely the NNI, on the knowledge flows and the nature of university research. Our contribution is not so much in demonstrating how such initiatives increase research productivity as in understanding how the initiatives influence the flows and the characteristics of university-generated knowledge. Noting that government initiatives seek to facilitate technology transfer from the university to the industry and promote a strong national innovation system, we examine the U.S. NNI that emphasizes the commercialization of nanotechnology and sets the directions for focused research. Our results reveal that the NNI has led to unintended consequences in knowledge production and dissemination. Specifically, we find that, for the U.S. universities, the NNI has increased knowledge inflows from the industry, diminished the branching-out to novel technologies, reduced the research scope, and generated fewer breakthrough outcomes in nanotechnology. None of these consequences appear consistent with the NNI's purported objectives.

These findings may remain open to alternative interpretations. Most important, the U.S. nanotechnology could have entered the steady state faster than other countries, independent of the NNI. Then, what we find might simply be capturing the normal progression of life-cycles which tend to exhibit over time diminished room for exploration and curtailed technological outcomes in both tails. However, our results show that, while successful technology outcomes (i.e., breakthroughs) in the U.S. university research significantly decrease, failures (i.e., left-tail outcomes) do not decrease in the post-NNI. If the technology life-cycle effect purely drove our results, failures should also have been reduced.

This asymmetry in the variance reduction in technological outcomes suggests that an exogenous source of variation such as the NNI launch has impacted the U.S. university research. The NNI may have generated this asymmetry by selectively funding high-potential research proposals, thereby leading to more successful outcomes. This in turn implies that the NNI effect should be greater on the right tail of distribution of technological performance, which is precisely what we find.

From the empirical standpoint, we claim two contributions. First, by identifying the NNI as a natural experiment and exploiting the difference-in-differences design, we improve our confidence in making causal inference from the findings. This is also our attempt to answer the call for a more precise identification based on counterfactuals in measuring the effect of policy interventions in the economics of science (Jaffe, 2006). Second, our econometric approach allows us to measure the changes in the landscape of research such as knowledge flows, new recombination, research scope, and the generation of breakthrough knowledge within universities as institutions of knowledge production. These changes may not necessarily bring short-term economic consequences but have long-term effects on the economy, which we do not directly examine in this paper. To the proposition that institutional changes imposed on the open science and the political patronage impact the long-term performance of the science and technology community (Dasgupta and David, 1994), we provide robust empirical evidence.

Our findings have a significant implication for science policies that pursue maximizing national economic benefits through mission-oriented initiatives. As Figure 11 presents, mission-oriented government initiatives may exert dual impacts on university research. Under the NNI, the mean value of university research clearly moved upward and the poor outcomes decreased, but the breakthrough outcomes decreased too. The government-initiated emphasis on commercialization and focused research directions may improve the average economic payoffs by increasing the outcome efficiency. However, these initiatives may undermine open paths toward novel technologies and hinder explorations of unknown fields, thereby reducing the chances of achieving breakthrough outcomes from university research.

These adverse impacts on university research may well spread to the entire research community, as indicated by the overall reduction in the U.S. institutions' branching-out to novel technologies in the post-NNI period. The U.S. research community, the beneficiary of knowledge spillovers from the U.S. universities, seems to have been affected indirectly by the post-NNI perturbation in the nature of university research. In particular, the restricted accessibility to the U.S. university research in the post-NNI period may have taxed the U.S. industry disproportionately more than it did to the non-U.S. industry by increasing the relative cost of accessing the channels of knowledge acquisition such as publications or formal/informal communications with university researchers (cf. Cohen et al, 2002). Increased secrecy and incomplete disclosure of university research findings raise the effective cost (such as searching, licensing fees and infringement liabilities) that industry researchers may bear to use these findings. Given the localization of knowledge spillovers (Jaffe, Trajtenberg, Henderson, 1993; Thompson, 2006), the cost increase following the NNI may have been much greater for the U.S. institutions than for the institutions outside the U.S. Our finding that the NNI have had greater adverse effects on the U.S. industry than on the non-U.S. industry renders support to this conjecture. In contrast, we find no difference between the U.S. universities and non-U.S. universities in branching-outs. Thus we further conjecture that the NNI has influenced the university research community beyond the national boundary but affected industry research only within the national boundary. If this were the case, an open question arises as to the effect of the NNI on the knowledge network structure of nanotechnology research among universities and firms. For example, does the NNI motivate the collaboration between universities and firms within or beyond the national boundary? How does the NNI influence the position of the U.S. institutions in that knowledge network?

Finally, one might be interested in whether government mission-oriented initiatives attain the social optimum but that is beyond the scope of this paper. After all, it depends on the policy decision that sets up objective functions in the domain of science and technology. However, our analysis generally underscores the importance of the immediate disclosure of research results and the autonomy of researchers in determining the priorities in conducting research in universities (Bush, 1945; Polanyi, 1962; Merton, 1973; Dasgupta and David, 1994; Nelson, 2004).

REFERENCES

OMITTED TO CONSERVE SPACE BUT AVAILABLE FROM THE AUTHORS.

Table 1 Summary Statistics

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
(1) Knowledge flows from industry ratio															
(2) Knowledge flows from indutry	0.333														
(3) Branching-out	-0.094	-0.051													
(4) log Subclasses	-0.042	-0.016	0.674												
(5) Subclasses	-0.032	-0.009	0.636	0.950											
(6) Top 5%	0.016	0.009	0.074	0.039	0.039										
(7) Z_norm	-0.015	0.008	0.075	0.041	0.037	0.720									
(8) Post NNI	0.074	0.093	-0.054	-0.042	-0.044	-0.228	-0.131								
(9) US	-0.072	0.068	0.048	0.025	0.020	0.079	0.113	0.056							
(10) University	-0.083	-0.038	0.043	0.029	0.021	0.040	0.083	0.070	0.256						
(11) Non patent reference	0.003	0.281	0.001	1.0E-4	-0.001	0.034	0.067	0.094	0.183	0.141					
(12) Claims	-0.004	0.025	0.010	0.002	0.002	0.103	0.111	-0.033	0.158	0.073	0.115				
(13) log Claims	0.001	0.025	0.001	-0.010	-0.008	0.095	0.120	-0.028	0.186	0.087	0.097	0.819			
(14) University-firm Copatent	0.005	0.026	-0.017	-0.010	-0.002	0.004	0.027	-0.003	0.035	0.219	0.021	0.034	0.032		
(15) Total backward citation	0.098	0.491	-0.015	-0.020	-0.022	0.040	0.070	0.063	0.186	-0.039	0.619	0.144	0.126	0.014	
Obs	5401	5401	5401	5401	5401	5401	5401	3720	5401	5401	5401	5401	5400	5401	5401
Mean	0.391	2.331	0.285	0.522	2.054	0.143	0.403	0.502	0.721	0.202	13.850	20.974	2.762	0.012	14.403
Std. Dev.	0.431	6.426	0.452	0.597	1.483	0.350	1.336	0.500	0.449	0.402	31.538	17.476	0.795	0.109	28.626
Min	0	0	0	0	1	0	-1.488	0	0	0	0	0	0	0	0
Max	1	95	1	2.773	16	1	20.647	1	1	1	436	296	5.690	1	406

Note: All correlation coefficients above 0.03 or below -0.03 are significant at 5%.

Table 2 Models for the effect of the NNI on university research

	(2-1)	(2-2)	(2-3)	(2-4)	(2-5)	(2-6)	(2-7)	(2-8)	(2-9)	(2-10)
D.V	Knowledge flow	Knowledge flow	Branching-out	Branching-out	log (Subclass)	Subclass	Top5%	z_norm	z_norm>0	z_norm<0
	OLS(Ratio)	NB	Logit	Logit	OLS	NB	Logit	OLS	OLS	OLS
PostNNI	-0.131***	-0.332***	0.053	0.378*	0.149***	0.142**	-4.547***	-0.407***	-1.069***	0.273***
	(0.036)	(0.121)	(0.189)	(0.228)	(0.048)	(0.058)	(1.022)	(0.087)	(0.133)	(0.025)
US University	-0.273***	-0.331***	0.573***		0.138***	0.137***	0.563***	0.366***	0.504***	0.015
	(0.032)	(0.097)	(0.127)		(0.036)	(0.039)	(0.148)	(0.105)	(0.150)	(0.020)
PostNNI*US University	0.100***	0.309***	-0.354**		-0.113**	-0.108*	-0.668**	-0.374***	-0.571***	0.002
	(0.039)	(0.116)	(0.178)		(0.047)	(0.055)	(0.327)	(0.108)	(0.153)	(0.024)
US				0.411***						
				(0.122)						
PostNNI*US				-0.484***						
				(0.177)						
Non Patent Reference	-0.001***	-0.003***					0.007***	0.003***	0.004***	1.35E-4
	(1.40E-4)	(0.001)					(0.001)	(0.001)	(0.001)	(1.04E-4)
Claims	-0.001**	-4.87E-4	0.003	0.003		0.001	0.014***	0.006***	0.003**	4.16E-4
	(3.61E-4)	(0.001)	(0.002)	(0.002)		(0.001)	(0.003)	(0.001)	(0.001)	(4.02E-4)
Log Claims					0.011					
					(0.012)					
University-firm Copatent	0.138**	0.513***	-0.483	-0.247	-0.087	-0.048	-1.061	-0.136	0.003	0.010
	(0.057)	(0.161)	(0.335)	(0.331)	(0.083)	(0.119)	(0.677)	(0.184)	(0.218)	(0.039)
Total Backward Citation		0.020***								
		(0.001)								
Constant	0.833***	1.088***	-1.232***	-1.430***	0.431***	0.646***	-1.727***	0.324***	1.182***	-0.411***
	(0.026)	(0.096)	(0.138)	(0.162)	(0.048)	(0.042)	(0.150)	(0.086)	(0.132)	(0.024)
Year effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R-squared	0.101				0.020			0.054	0.176	0.218
Log-likelihood		-4805.533	-2105.143	-2110.175		-6007.495	-1090.522			
N	2135	2135	3720	3720	3720	3720	3720	3720	2201	1519

* p<0.10 ** p<0.05 *** p<0.01

Robust standard errors in parentheses

Table 3 Models for the effect of the NNI estimated on subsamples (University and the U.S.)

	(3-1)	(3-2)	(3-3)	(3-4)	(3-5)	(3-6)	(3-7)	(3-8)	(3-9)	(3-10)
Data set	University	US	University	US	Firms	University	US	US	University	US
D.V	Knowledge flow	Knowledge flow	Branching-out	Branching-out	Branching-out	log (Subclass)	log (Subclass)	Top5%	z_norm	z_norm
	OLS(Ratio)	NB	Logit	Logit	Logit	OLS	OLS	Logit	OLS	OLS
PostNNI	-0.250*	-0.117***	-0.411	-0.090	0.600**	0.338	0.144**	-4.507***	0.104	-0.558***
	(0.143)	(0.042)	(0.895)	(0.215)	(0.263)	(0.215)	(0.056)	(1.024)	(0.320)	(0.109)
US	-0.416***		0.554		0.420***	0.287*			0.976***	
	(0.062)		(0.714)		(0.137)	(0.158)			(0.175)	
PostNNI*US	0.335***		-0.349		-0.601***	-0.356*			-0.988***	
	(0.104)		(0.829)		(0.202)	(0.189)			(0.188)	
University		-0.262***		0.477***			0.129***	0.359**		0.241**
		(0.033)		(0.134)			(0.037)	(0.152)		(0.111)
PostNNI*University		0.087**		-0.211			-0.097*	-0.641*		-0.233**
		(0.040)		(0.188)			(0.049)	(0.329)		(0.114)
Non Patent Reference	-0.001***	-0.001***						0.007***	0.85E-4	0.003***
	(2.92E-4)	(1.40E-4)						(0.001)	(0.001)	(0.001)
Claims	-0.001*	-0.001	0.003	0.003	0.002			0.012***	0.007***	0.005***
	(0.001)	(0.000)	(0.004)	(0.002)	(0.002)			(0.002)	(0.002)	(0.001)
Log Claims						0.007	0.020			
						(0.028)	(0.014)			
University-firm Copatent	0.151***	0.172***	-0.539	-0.415	-0.151	-0.110	-0.054	-1.000	-0.143	-0.195
	(0.056)	(0.053)	(0.352)	(0.359)	(0.333)	(0.088)	(0.098)	(0.645)	(0.191)	(0.224)
Constant	0.883***	0.818***	-1.118	-1.116***	-1.466***	0.298	0.412***	-1.449***	-0.134	0.475***
	(0.106)	(0.034)	(0.769)	(0.159)	(0.183)	(0.190)	(0.058)	(0.167)	(0.313)	(0.107)
Year effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R-squared	0.093					0.031			0.077	0.059
Log-likelihood		-549.651	-498.802	-1585.733	-1457.744		-2389.059	-887.006		
N	524	1619	838	2762	2652	838	2762	2762	838	2762

* p<0.10 ** p<0.05 *** p<0.01

Robust standard errors in parentheses

Note : We do not report the regression of Top5% using university data set because the non-U.S. universities do not have patents with top 5% forward citations.

Table 4 Models for the effect of the NNI with different time windows

	(4-1)	(4-2)	(4-3)	(4-4)	(4-5)	(4-6)	(4-7)	(4-8)
	4 year window				6year window			
D.V	Knowledge flow	Branching-out	log (Subclass)	Top5%	Knowledge flow	Branching-out	log (Subclass)	Top5%
	OLS(Ratio)	Logit	OLS	Logit	OLS(Ratio)	Logit	OLS	Logit
PostNNI	-0.117***	-0.071	0.041	-3.716***	-0.160***	0.072	0.122**	-4.705***
	(0.034)	(0.189)	(0.045)	(0.731)	(0.046)	(0.224)	(0.057)	(1.024)
US University	-0.258***	0.571***	0.142***	0.557***	-0.249***	0.563***	0.127***	0.647***
	(0.033)	(0.139)	(0.038)	(0.164)	(0.030)	(0.121)	(0.034)	(0.136)
PostNNI*US University	0.090**	-0.230	-0.095*	-0.616*	0.068*	-0.358**	-0.091**	-0.762**
	(0.041)	(0.195)	(0.051)	(0.333)	(0.037)	(0.169)	(0.045)	(0.321)
Non Patent Reference	-0.001***			0.007***	-0.001***			0.008***
	(1.42E-4)			(0.001)	(1.35E-4)			(0.001)
Claims	-0.001**	0.002		0.013***	-0.001*	0.003		0.014***
	(3.89E-4)	(0.002)		(0.003)	(3.63E-4)	(0.002)		(0.002)
Log Claims			0.009				0.008	
			(0.013)				(0.012)	
University-firm Copate	0.168***	-0.804**	-0.149*	-1.207	0.132**	-0.517	-0.103	-0.523
	(0.051)	(0.400)	(0.087)	(0.775)	(0.055)	(0.319)	(0.078)	(0.508)
Constant	0.838***	-1.320***	0.430***	-2.012***	0.822***	-1.344***	0.431***	-1.568***
	(0.026)	(0.148)	(0.051)	(0.169)	(0.033)	(0.161)	(0.051)	(0.160)
Year effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R-squared	0.097		0.020		0.098		0.019	
Log-likelihood		-1742.161		-923.657		-2356.471		-1220.957
N	1773	3083	3083	3083	2388	4184	4184	3960

* p<0.10 ** p<0.05 *** p<0.01

Robust standard errors in parentheses

Note: In model 4-8, observations reduce to 3,960 because observations of year 2007 predict all failure and were omitted.

Figure 1. The NNI investment

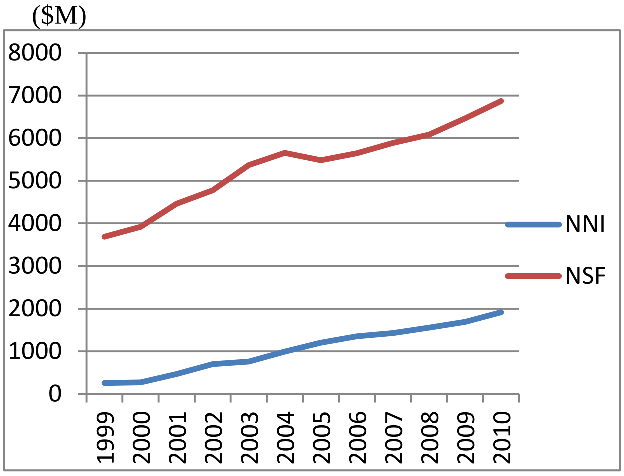


Figure 2. The NNI funding growth rate

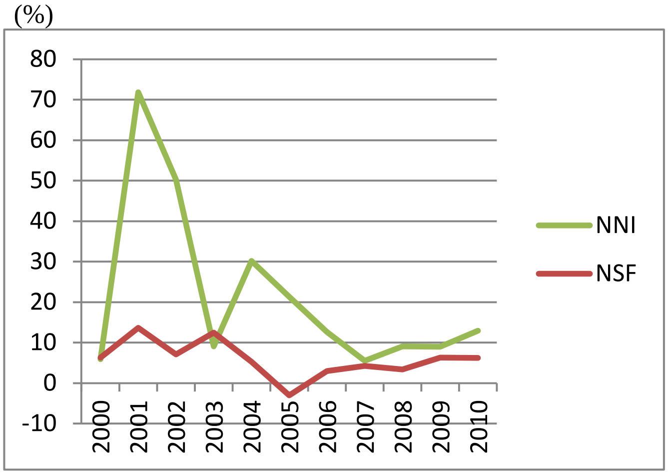
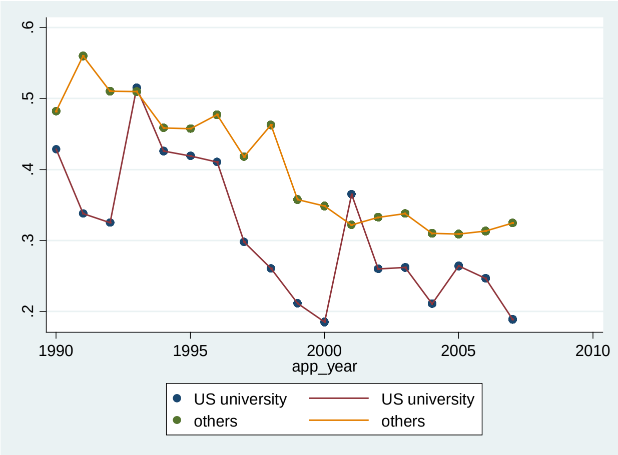
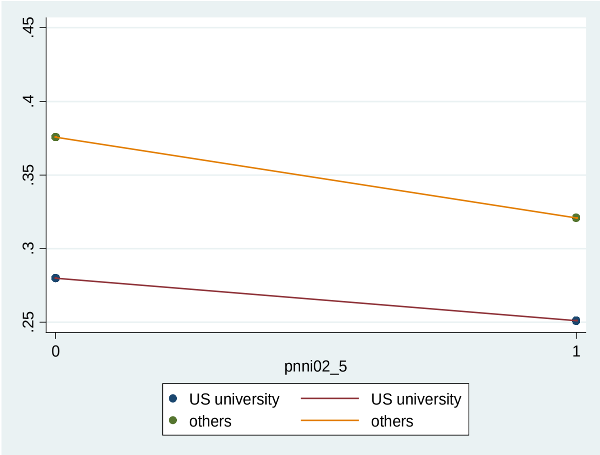


Figure 3. Knowledge flows from industry



Note: Each point represents the ratio of backward citations to industry nanotechnology patents over all backward citations to nanotechnology patents.

Figure 4. Comparison of knowledge flows from industry between the pre- and post-NNI



Note: '0' stands for pre-NNI and '1' for post-NNI.

Figure 5. The branching-out to novel Recombination

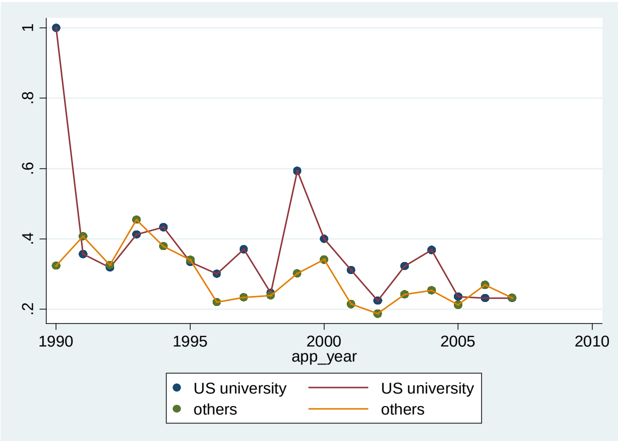
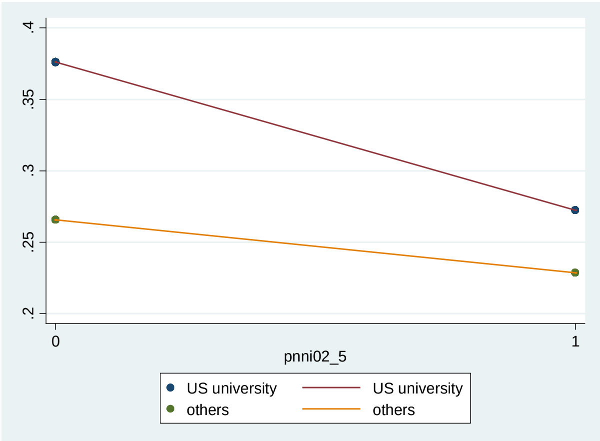


Figure 6. Comparison of the branching-out to new recombination between the pre- and post-NNI



Note: '0' stands for pre-NNI and '1' for post-NNI.

Figure 7. Nanotechnology research scope

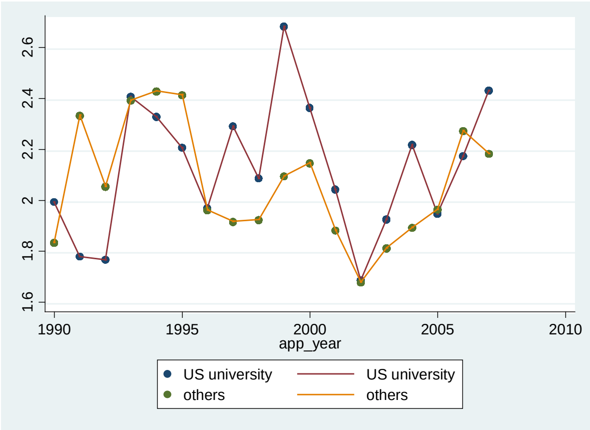
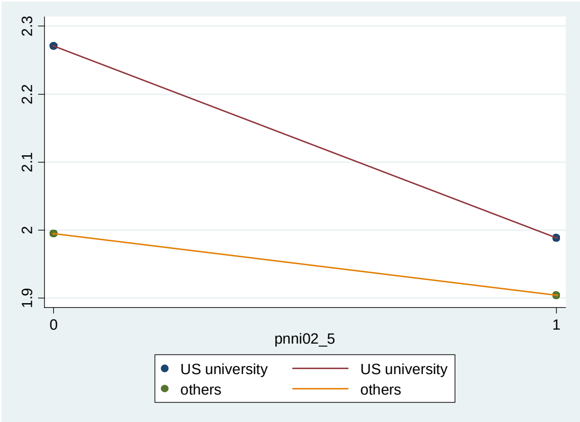


Figure 8. Comparison of the nanotechnology research scope between the pre- and post-NNI



Note: '0' stands for pre-NNI and '1' for post-NNI.

Figure 9. The proportion of breakthroughs in nanotechnology

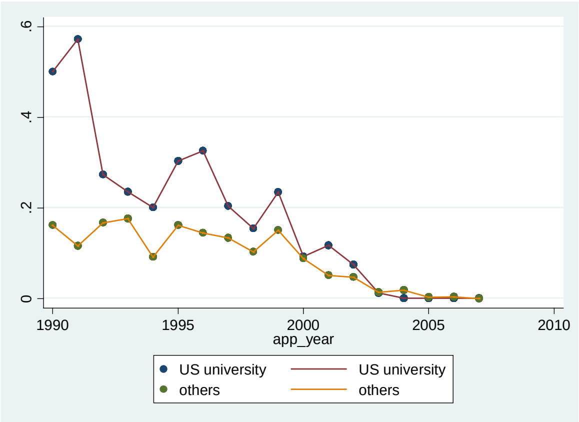
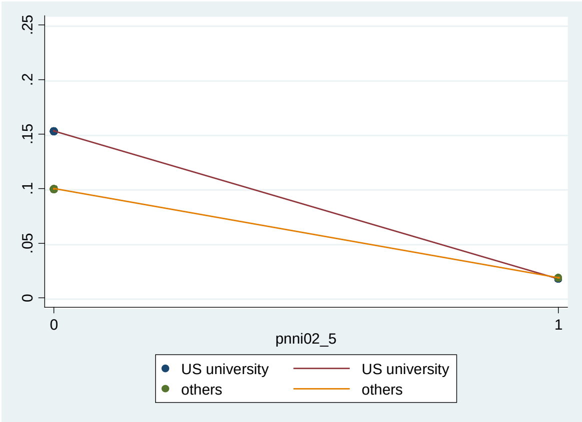
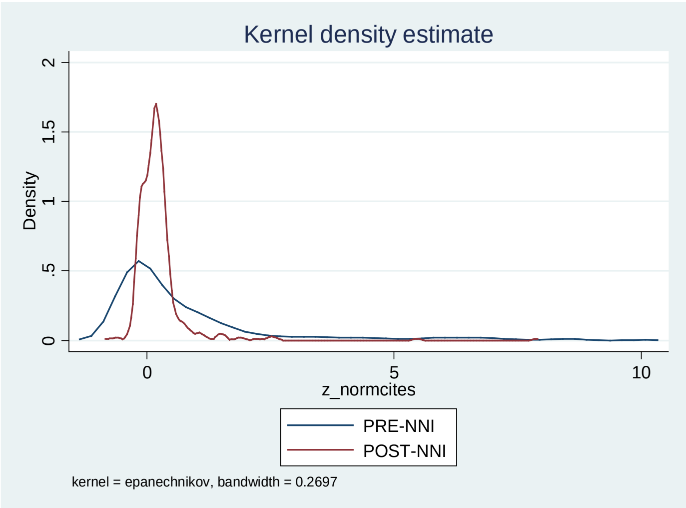


Figure 10. Comparison of the proportion of breakthroughs in nanotechnology research between the pre- and post-NNI



Note: '0' stands for pre-NNI and '1' for post-NNI.

Figure 11. Comparison of distribution of the number of forward citation between the pre- and post-NNI



Notes. Z_normcites is the standard normalized number of forward citations made to nanotechnology patents as compared to patents applied for and granted in the same year and in the same technology class.

<Appendix 1>

List of Federal Agencies Participating in the NNI During 2011 (NNI-Supplement to the President's FY 2012 Budget)	
Federal agencies with budgets dedicated to nanotechnology research and development	2010 actual budget (dollars in millions)
Consumer Product Safety Commission (CPSC)	0.5
Department of Defense (DOD)	439.6
Department of Energy (DOE)	373.8
Department of Homeland Security (DHS)	21.9
Department of Justice (DOJ)	0.2
Department of Transportation (DOT, including the Federal Highway Administration, FHWA)	3.2
Environmental Protection Agency (EPA)	17.7
Food and Drug Administration (FDA, Department of Health and Human Services)	7.3
Forest Service (FS, Department of Agriculture)	7.1
National Aeronautics and Space Administration (NASA)	19.7
National Institute for Occupational Safety and Health (NIOSH, Department of Health and Human Services/Centers for Disease Control and Prevention)	8.5
National Institute of Food and Agriculture (NIFA, Department of Agriculture)	13.2
National Institute of Standards and Technology (NIST, Department of Commerce)	114.7
National Institutes of Health (NIH, Department of Health and Human Services)	456.8
National Science Foundation (NSF)	428.7
Other participating agencies	
Bureau of Industry and Security (BIS, Department of Commerce)	
Department of Education (DOEd)	
Department of Labor (DOL, including the Occupational Safety and Health Administration, OSHA)	
Department of State (DOS)	
Department of the Treasury (DOTreas)	
Director of National Intelligence (DNI)	
Nuclear Regulatory Commission (NRC)	
U.S. Geological Survey (USGS, Department of the Interior)	
U.S. International Trade Commission (USITC)	
U.S. Patent and Trademark Office (USPTO, Department of Commerce)	

Source: NSTC, Supplement to the President’s FY2012 Budget, 2011

<Appendix 2>

NANOTECHNOLOGY (PCA 4)

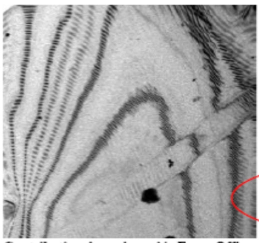
4D Electron Microscope for Directly Visualizing Atomic-scale Motion

A breakthrough technology allows, for the first time, the real-time visualization of fleeting changes in the structure and shape of matter barely a billionth of a meter in size. The new technique, named four-dimensional (4D) electron microscopy, was developed at the Caltech Physical Biology Center for Ultrafast Science and Technology under the direction of Nobel Prize-winner Ahmed Zewail.

Researchers can observe the static structure of objects with resolution better than a billionth of a meter in length using electron microscopes, which generate a stream of individual electrons that scatter off objects to produce an image. Zewail and his colleagues introduced time into high-resolution electron microscopy by releasing electrons at specific time intervals and precisely controlling their trajectories. Each electron results in a still image, and the sequential images generated by millions of electrons can be assembled into a digital movie of atomic scale motion.

Zewail's team used 4D electron microscopy to observe the behavior of the atoms in extremely thin sheets of graphite. The layers of carbon atoms in graphite move in a unique and coherent way on the femtosecond timescale; on the picosecond scale, the graphite nanosheets produce sound waves. Researchers directly visualized the elastic movements of the sheets and determined the force holding them together. They also visualized the changes in a nanometer-thick graphite membrane on a timescale up to a thousandth of a second. After being heated, the carbon atoms vibrated randomly, but over time the oscillations of the individual atoms became synchronized into a heartbeat-like "drumming."

This technique for directly visualizing atomic-scale motions will enable greater understanding of structural, morphological, and nanomechanical phenomena. It can also be used for biological imaging of cell components, such as proteins and ribosomes.



Nano-drumming of graphite, visualized with 4D microscopy. (Nano Letters; image produced at Caltech)

O.-H. Kwon, B. Barwick, H.S. Park, J.S. Baskin and A.H. Zewail. Nanoscale Mechanical Drumming Visualized by 4D Electron Microscopy, *Nano Lett.* **8**, 3557 (2008).

B. Barwick, H.S. Park, O.-H. Kwon, J.S. Baskin, and A.H. Zewail. 4D Imaging of Transient Structures and Morphologies in Ultrafast Electron Microscopy, *Science* **322**, 1227 (2008).

Patents or other steps toward commercialization: A patent on the conceptual framework of this approach was granted to the California Institute of Technology (Caltech) in 2006.

Contributing Agencies: Air Force Office of Scientific Research, NIH, and NSF