The Impact of the Investment in Nano at Purdue University: Peer-reviewed Publications as a Metric

In the year 2000, Purdue University and its stakeholders decided to make a significant investment in nanoscience, nanoengineering, and nanotechnology (abbreviated as "nano" in this document). At that time, Purdue was known for theory and simulation in nanoelectronics and in niche areas of experimental nanoscience. Within a brief period from 2000 to 2002, Purdue's nano effort was boosted by four significant events: 1) the creation of Discovery Park, including plans for the $58M Birck Nanotechnology Center, 2) the expansion of the faculty, which would ultimately result in approximately twenty new faculty positions in nanoscience and nanoengineering, 3) an award from NSF to launch the Network for Computational Nanotechnology (NCN), and 4) an award from NASA to create the Institute for Nanoelectronics and Computing (INAC). These four almost simultaneous events created the foundation for a vibrant academic research program in nano that is still evolving rapidly today. Some eight years later, we are now in a position to look back at these formative years and evaluate the progress that has resulted from an investment that totals approximately $150M.

Progress can be measured by a combination of publications, citations, national awards, research expenditures, graduate degrees completed, patents filed, companies started and several other worthy metrics. Of these, we focus here on publications in peer-reviewed journals that are included in the Science Citation Index (SCI). Although other metrics may be better measures of the value and impact of research, publications are countable within a year following the onset of a research program. Citations, patents, and graduate degrees all require several years to assess. Research expenditures and grant awards are input and not output.

The following analyses are derived from searches performed with the Thomson ISI Web of Science database. Search fields were limited to Topics, Address, and Year Published. These analyses present a descriptive and quantitative picture of the impact of the investment in nanotechnology research at Purdue.

These analyses were presented during the 2nd Annual Birck Nanotechnology Center Research Review, April 14th, 2008. Timothy D. Sands, the Mary Jo and Robert L. Kirk Director of the Birck Nanotechnology Center, is responsible for these analyses and any errors or omissions. The network diagrams were prepared by Jeff Goecker, Communications Specialist for the BNC.

Nano Research in the Midwest

Before delving into the nano publication record of Purdue University, it is interesting to note the leading role of Midwestern academic institutions in nanotechnology research in the U.S. The claim that the Midwest is a major player in nanotechnology may come as a surprise to some, as it is widely perceived that nanotechnology is a coastal phenomenon. In fact, Midwestern universities, especially those in the Big Ten, have long been leaders in nanotechnology, well before the public recognition of this "superdiscipline" in 2000.Figure 1 shows the geographic breakdown of the publications in nano by U.S. universities in the 2007 calendar year. These data were acquired by setting Topic = nano*, identifying the universities with more than 50 such publications in 2007 (41 universities total), and then sorting these institutions by geographic region. A total of 6,836 publications were included. Note that setting Topic = nano* is an objective, but flawed search criterion. Some authors working on nano topics may elect not to use the prefix, while others may be using nano- to describe work that most in the field would not consider as nano. Also, because the list of universities included was truncated at a level of 50 publications, it is possible that a large number of smaller programs in one region may be dismissed, thereby skewing the results. These caveats aside, the analysis shows that the contributions of the Midwest's academic institutions to nanotechnology publications exceed those of any other geographical region. It would be interesting to perform a similar analysis of the geographic distribution of the federal government's investments in nano research.

Geographical Distribution of 2007 Nano Publications

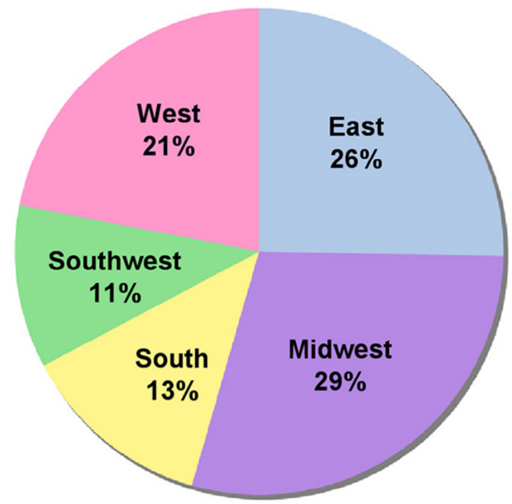

Figure 1 – Geographic breakdown of 2007 publications in nano by U.S. academic institutions. The Big Ten universities contribute more than a quarter of all nano publications.

Looking more closely at the Midwest's contribution, it is dominated by the Big Ten universities. Eight of the Big Ten institutions had more than 50 nano publications in 2007, totaling 1,829 out of the 2,003 publications from the region - approximately 27% of the nation's total.

Nano Research by Institution

In an effort to assess the impact of the investment in nano at Purdue University, the publication output of 31 institutions with more than 100 nano (Topic = nano*) publications in 2007 was tallied for both 2002 and 2007. The bar charts in Figure 2 show that Purdue rose from #15 to #7 during this five-year span, coinciding with the major investments in facilities, centers and faculty positions. It is interesting to note that the total number of publications more than doubled in this five-year period. The number of Purdue nano publications increased by 242%. Five Big Ten universities were among the top ten in 2007.

Another way to look at these data is to consider the percentage change in publication rate. The table below shows that among the 27 universities with more than 50 nano publications in 2002 (i.e., established programs in 2002), Purdue showed the greatest percentage increase in nano publications between 2002 and 2007. This is perhaps the clearest evidence for the impact of the investment in nano at Purdue.

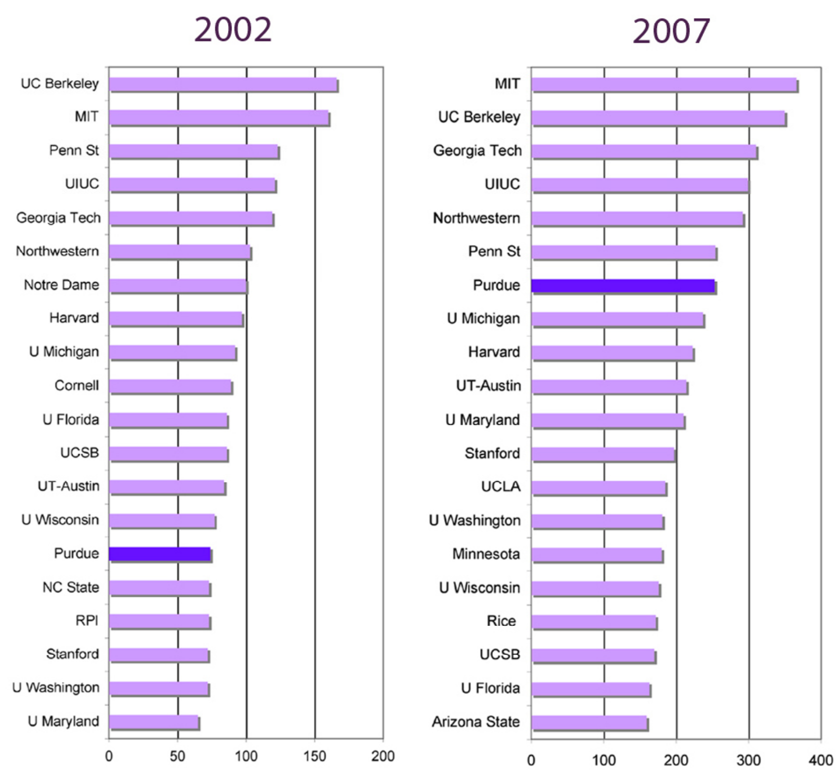

Figure 2 – Ranking of U.S. academic institutions by number of publications in nano in 2002 (left) and 2007(right) (Web of Science database; Topic = nano*).

How has the investment in new faculty and the $58M BNC facility impacted the research community in nano at Purdue? The answer to that question is complex, and a simple metric such as number of publications only begins to offer any insight. A more complete picture will emerge in several years as the impact on science (e.g., citations and awards), students (Ph.D. graduates and undergraduate research experiences), and technology delivery (patents, licenses, spin-off companies, and industry sponsored research) are assessed. For now, we look at publications as a measure not only of research productivity, but also of collaboration.

The Timeline: The Birck Nanotechnology Center grew out of a need for modern cleanroom space for semiconductor research in the 1990's. Electrical engineering researchers at Purdue had developed a reputation as one of the leading groups in the U.S. The facilities, however, lagged well behind those of their competitors. By the time that former President Martin Jischke arrived at Purdue in 2000, the EE faculty members had developed a detailed plan for a new building.

Purdue	242
Rice	237
UCLA	236
U Maryland	223
Northwestern	183
Minnesota	177
Stanford	174
Arizona State	165
U Penn	161
Georgia Tech	161
U Michigan	158
UT-Austin	155
U Washington	151
UIUC	147
Ohio State	142
Harvard	130
U Wisconsin	129
MIT	129
Caltech	122
UC Berkeley	111
Penn St	107
NC State	104
UCSB	98
U Florida	90
RPI	88
Cornell	73
Notre Dame	6

Table 1 – Percent increase in nano publications from 2002 to 2007 for institutions with 50 or more nano publications in 2002

Recognizing an opportunity to raise private funds with a broader scope, President Jischke adopted the plans as the foundation for one of the first Centers in Discovery Park. The BNC became a "virtual" center in March of 2001. By Fall 2001, $51M had been raised for the Birck Nanotechnology Center building, most of it from private donors. The building was dedicated in October of 2005. Much of 2006 was occupied by the complex process of installing 185 tools, some newly acquired with resources from the Lilly Foundation, and others moved from buildings in other parts of campus. By November 2006, most of the labs and tools were up and running, and many of the residents were spending significant time in the building. In summary, the BNC became a virtual center in 2001, and a physical space for collaboration in late 2006. As of the writing of this report in April 2008, the BNC has been operating in the manner originally envisioned for approximately 17 months.

Figure 3 shows the number of BNC journal publications in the Web of Science database for each calendar year since 2003. These publications with Address = birck nano* represent those

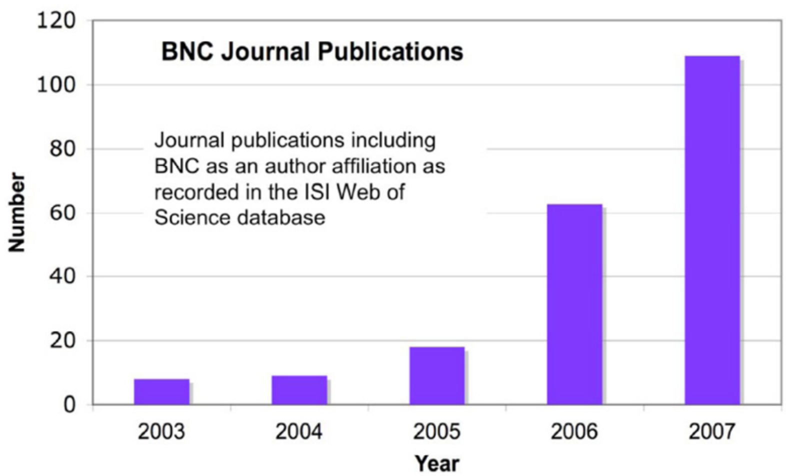

Figure 3 – BNC journal publications per year.

for which an author voluntarily elected to include the BNC as an affiliation, usually along with their primary academic unit. Many BNC residents also perform research outside the nano domain, and thus do not always include the BNC as an affiliation. Note also that these numbers have not been filtered by topic, although most of these papers involve nano. The fact that some of the reported research may not be considered to fall into the domain of nano reflects the fact that the BNC spans nano and microtechnologies in recognition of the fact that these two length scales are not always separable. Nano and micro researchers often use the same tools, and many nanotechnologies must exist within a microscale platform. The fact that the number of BNC-affiliated publications has grown markedly, especially since the building was occupied, may be attributed to a combination of enhanced research activity, and an increasing identification of the BNC researchers with the BNC as a community.

These publication data can also be mined more deeply to explore the degree to which they represent collaborative activities. To that end, we have examined the publications tallied in Figure 3 for the calendar years 2006 and 2007. Those publications involving two or more faculty members, research faculty or staff scientists who are affiliated with the BNC are displayed in the form of network diagrams in Figure 4. Darker, wider lines links represent a larger number of joint publications. Each faculty member or staff scientist who published jointly is represented as a "hub". It is important to note that each hub really represents a research group, and much of the work must be attributed to graduate students who are often first authors, and who may be credited with initiating many of the joint research activities through their daily interactions with students from other groups who occupy the same physical space.

The network diagrams in Figure 4 offer a qualitative sense of the evolving collaborative environment in the BNC community. It is evident that several groups were collaborating with large numbers of groups in 2007. The network has grown denser and more interconnected. It is also clear that there are opportunities remaining to better connect the smaller "sub-networks." Following the evolution of the BNC community through these diagrams over the next several years will help to assess the role of shared physical space, external funding for research centers, and internal initiatives for linking the sub-networks and seeding new ones.

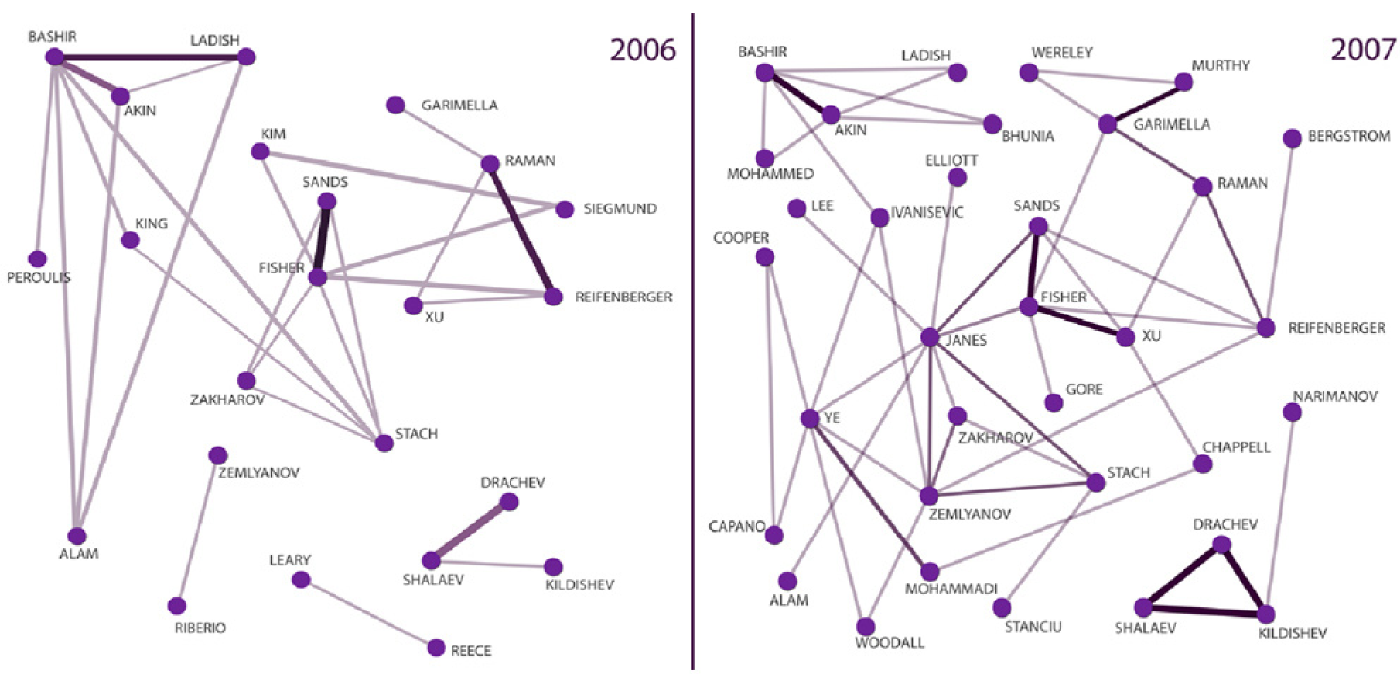

Figure 4 – Network diagrams portraying BNC collaborative research in 2006 and 2007. The "hubs" are BNC-affiliated faculty and staff scientists who published BNC-affiliated papers in the calendar year with at least one other BNC-affiliated faculty member or staff scientist. Darker and thicker links indicate a greater number of joint publications.

An Experiment: From a Virtual Center to "Real" Center

An important question to address is the role of shared physical space in building a research community. Most interdisciplinary communities are formed first as "virtual" centers, connected by shared interests, a seminar series, seed grant programs, and occasional meetings. It is relatively rare that a virtual center graduates to shared physical space, as the investment required is often daunting, and the potential negative impact on the academic units that "provide" the humanresources for the center can be an impediment. In the case of the BNC, the university and its stakeholders made this commitment, recognizing that an advanced facility is essential to performing experimental nano research. The fact that the BNC is more than a user facility is a credit to those who were involved at the conception stage. In fact, the co-location of people and tools may prove to be the single most important decision in the creation of the BNC.

With more than a full calendar year of operation of the BNC in shared physical space, we have the first opportunity to assess the impact of that shared space on research productivity and collaboration. We have considered only those 46 faculty members who were residents of the BNC in 2007 (occupied an office, had students desks in the building, or were considered the faculty-in-charge for equipment or space in the BNC), including all of their SCI publications in both 2005 (before occupancy) and 2007 (after occupancy). Figure 5 displays pie charts representing the total number of publications, and breaking those totals down into joint vs. single-group publications, as well as BNC-affiliated and non-BNC-affiliated publications.

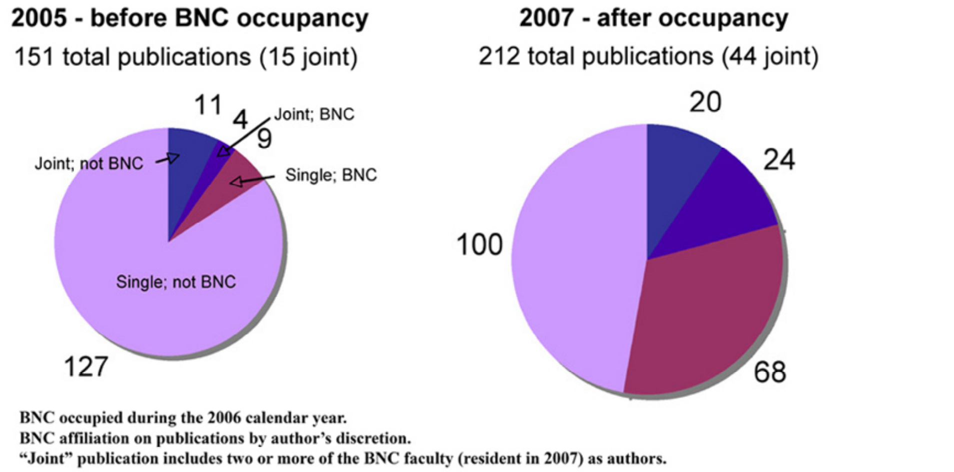

Figure 5 – Analysis of the publication of 46 BNC resident faculty before (2005) and after (2007) occupancy of the BNC building. 2006 was omitted as most of the year was occupied with moving tools and people into the BNC and setting up laboratories.

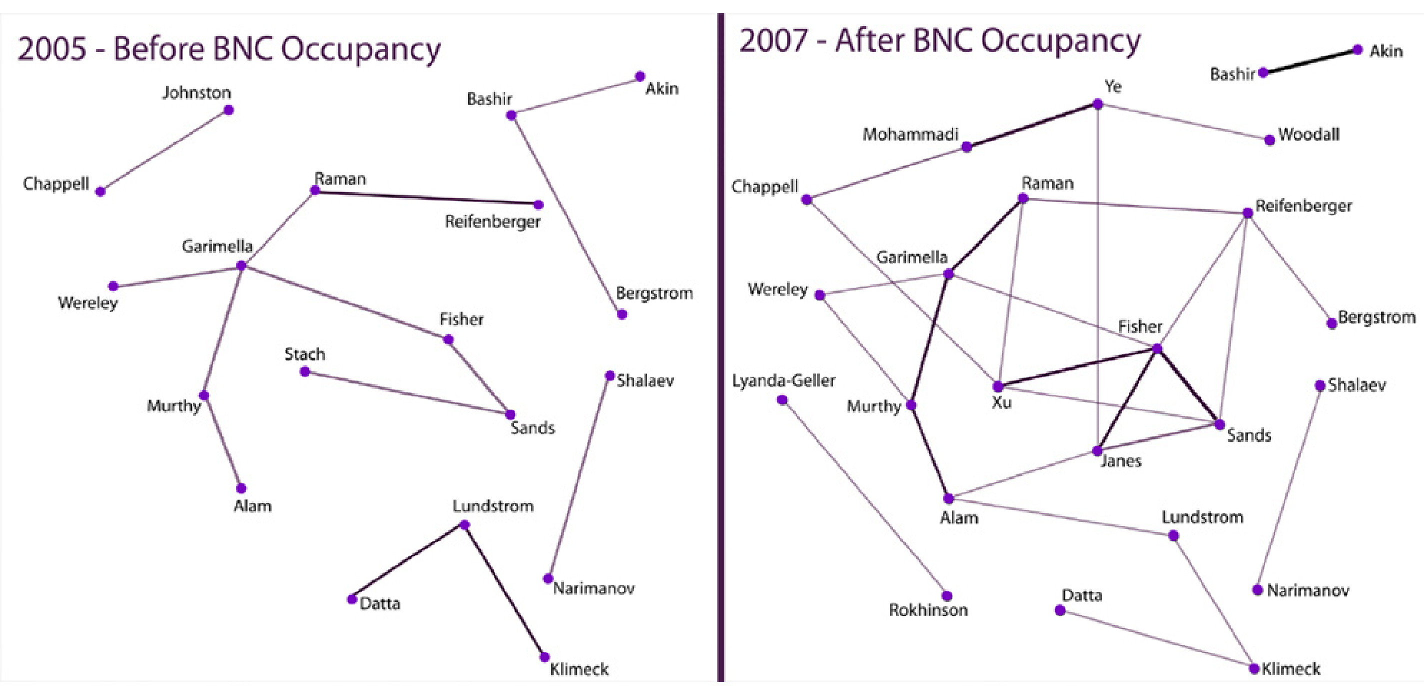

Figure 6 – Network diagrams for BNC resident faculty before and after occupation of the BNC building.

It is evident that the total number of publications by these 46 faculty members increased by 40%. More importantly, the number of joint publications more than tripled. It is difficult to assess the confounding effects of careers ramping up, as many of the faculty members were hired since 2002 (17 of the 30 residents with primary offices in the BNC). Nevertheless, the dramatic increase in joint publications likely reflects the impact of faculty members and their research groups working in the same space.

The evolution of the collaborative environment can also be studied through the network diagrams of Figure 6. These network diagrams depict the joint publications between groups among the publications tallied in Figure 5. A denser, more interconnected research community has emerged with the occupancy of shared physical space.

Conclusions

Through a straightforward analysis of publications in SCI journals, the impact of the investments made in Purdue's nano research environment has been assessed. Despite the limitation of this metric, the results strongly support the following conclusions, each of which should be tested further in the future employing a comprehensive set of the more slowly evolving metrics.

• Researchers at Midwestern universities contributed 29% of all U.S. publications in nano from academic institutions in the 2007 calendar year, the largest share from any geographical region.

• Researchers at Big Ten institutions were responsible for more than one in four of all U.S. publications in nano from academic institutions in 2007.

• Among all U.S. universities with established nano programs in 2002, Purdue has shown the greatest percentage increase in publication numbers from 2002 to 2007 (242%).

• The significant investments in Purdue's nano research program have dramatically increased research productivity and collaboration among researchers. In particular, the shared physical space and advanced facilities of the Birck Nanotechnology Center have markedly enhanced the research environment for nano at Purdue.