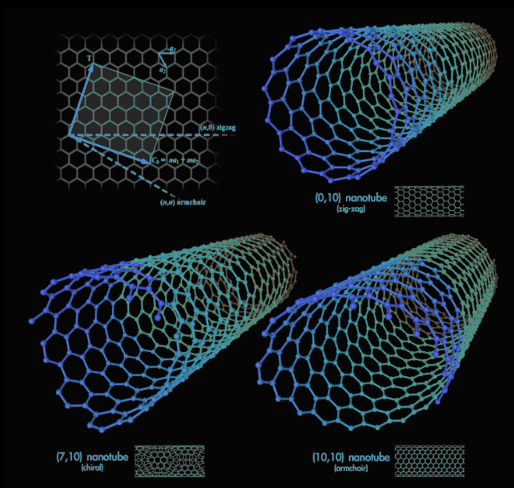
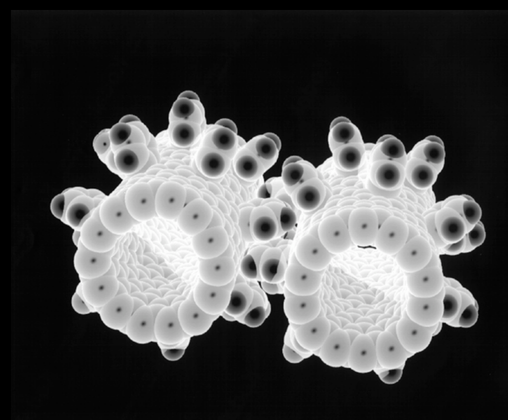
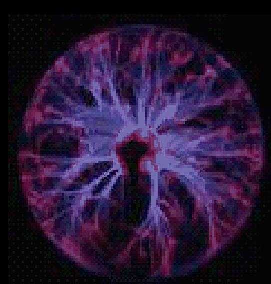
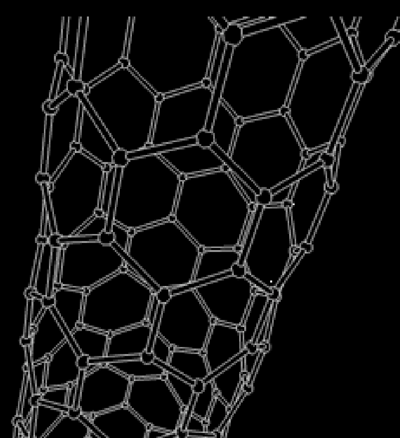
Report on Knowledge Transfer Activities in Connection with Nanoscale Science and Engineering
Final Report









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Report on Knowledge Transfer Activities in Connection with Nanoscale Science and Engineering

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Report on Knowledge Transfer Activities in Connection with Nanoscale Science and Engineering[1]

Executive Summary

The National Science Foundation plays a key role in the creation and growth of the U.S. nanoscale science and engineering (NSE) research community. Part of this mission is being accomplished through two collaborative research and education support programs and two user facility awards funded by the National Science Foundation that are the focus of this report. The two research and education programs studied are:

- The Nanoscale Interdisciplinary Research Teams (NIRT)
- The Nanoscale Science and Engineering Centers (NSEC)

The two user facility awards studied are:

- The National Nanotechnology Infrastructure Network (NINN)
- The Network for Computational Nanotechnology (NCN)

These activities are to some extent experimental because they are intended to meet the needs of the unusual and dynamic scientific and engineering research, education, and other activities characteristic of NSE. All four activities are components of a broader NSE program operated by NSF from FY 2001 through FY 2005. The NSE program has many unique elements, notably the design of NIRT awards, which fund collaborations of three to five Principal Investigators (PIs) having a blend of expertise from different research fields, often from a mix of departments and institutions. NSF asked SRI to examine the research and education outcomes of the four activities in the interval FY 2000 – FY 2005.

These activities represent about one-third of the budget for the NSF Nanoscale Science and Engineering priority area, which has been funded since FY 2001 and is currently operating at about $338 million for FY 2006. The goals of NSE are to support fundamental knowledge creation across disciplinary concepts and tools at the nanoscale, and to catalyze synergistic science and engineering research and education in emerging areas of nanoscale science and technology.

To describe the knowledge transfer activities and outputs of the four activities, it is necessary to identify appropriate input, activity, and output measures that capture the unique features of NSE. Priority categories of program or award knowledge transfer activity and output are examined in this report. These categories, listed in the order in which results are presented in the different sections, are:

- Research Outputs
- Collaborations
- Economic Impact

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[1] We wish to acknowledge the cooperation of NSF award principal investigators, who provided additional information and insights into the data they report formally to NSF; to Mike Roco and Jo Culbertson for their valuable guidance in making this report more accurate and useful; and to Robin Skulrak and Adrian Tyler for invaluable assistance in making the report more readable as well as accurate.

- Interdisciplinarity
- Education and Training
- Societal, Ethical, Environmental, Health and Safety Implications.

Data are drawn from interviews with principal investigators, from written reports from the four NSF-funded activities, Websites, and from NSF databases.

For the four activities studied, to the extent possible quantitative indicators of knowledge transfer were collected and analyzed. For those parts of the activities focusing on research, economic impacts, interdisciplinarity, and education, quantitative indicators are presented. For the parts of the activities focusing on environmental or societal implications, quantitative indicators are not available, but qualitative information is presented.

Key quantitative findings for each of the four NSF-funded activities are presented below.

The Nanoscale Interdisciplinary Research Teams – NIRTs (total 259 awards)

- Since the program was initiated in FY 2001 and through FY 2004, all NIRT awards have produced a cumulative total of 1,086 publications in refereed technical journals.
- Typical NIRT awards increased their publication output each year; the 44 FY 2001 awardees report an average output of 26 publications per award in FY 2004, the year they filed their final reports.
- During FY 2001-FY 2004, both the total number of organizational partners per year and the number of individual collaborators per award increased over time; for the FY 2001 cohort of awards, the number of partners increased from 42 to 71 and the number of partners per award increased from 1.3 to 3.4.
- During FY 2001-FY 2004, 31 percent of awards reported some form of technology transfer output: invention disclosures (109), patents filed (87) and patents awarded (9).
- 11 spin-off companies emerged from NIRT awards during FY 2001-FY 2004.
- For FY 2001-FY 2004, the average number of departments represented on awards was 2.75, indicating interdisciplinary coordination.
- During the same period, 459 degrees were granted as a result of NIRT activities: B.A.s (135), M.A.s (128), and Ph.D.s (195).
- During FY 2001-FY 2004, nearly 50 percent of NIRT awards contributed to curriculum development.

The Nanoscale Science and Engineering Centers – NSECs (total 14 awards)

- NSEC-related research resulted in 1,822 publications in refereed technical journals over the period 2001-2005.
- In 2005, the 6 NSECs in the first cohort (2001) of awards produced an average of 74 publications per center in peer reviewed technical journals.
- Over 2001-2005, 91 percent of NSEC-related publications were co-authored.
- Most NSEC sites reported relationships with more than ten partnering institutions over the reporting period 2001-2005.
- NSEC activities during 2001-2005 resulted in formal technology transfer outputs that included 175 inventions disclosed and 179 patent filings.

- During 2001-2005, 258 degrees were granted as a result of research at NSECs: B.A.s (53), M.A.s (57), Ph.D.s (148).
- NSECs offered 862 workshops and short courses during 2001-2005: 123 to industry and 739 to others.
- 149 of the 413 faculty participating in NSECS during 2001-2005 list more than one departmental affiliation.
- Participants in NSECs during this period were drawn from ten different departments, led by Chemistry and Chemical Engineering.
- 17 spin-off companies emerged from NSEC-related activities during 2001-2005.
- Industry support totaled $15 million over five years, an indication of the economic value of the centers to industry.

The National Nanotechnology Infrastructure Network – NNIN (total 13 nodes)

- In operation only since March 2004, 1,734 papers related to NNIN were published or presented at conferences in the 17 month period ending July 2005.
- 89 percent of these papers had more than one author, suggesting collaboration.
- Partners in NNIN activities were drawn from 11 different academic fields, led by materials science and MEMS.
- The cost of lab use per hour averaged $30 for the period March 2005-February 2006. This relatively low cost suggests that NNIN has been efficient in providing NSE infrastructure.
- NNIN trained over 4,140 users and students during March 2005-February 2006.
- More than 3,200 graduate students per year have conducted research at NNIN facilities.
- 32 spin-off companies emerged from NNIN-supported activities during March-December 2005.
- For March 2004-February 2006, industry represented 14-15 percent of users, with small companies representing 10-11 percent, a larger percentage than big companies.
- NNIN sites collected $16 million in user fees during March 2005-February 2006; half the users were self-funded.
- NNIN workshops in 2005-2006 hosted more than 700 people.

The Network for Computational Nanotechnology – NCN (total 7 nodes)

- During September 2003 through June 2006, NCN has deployed 40 simulation tools and more than 50 different educational resources on NanoHUB, whose users now number 12,000+ per year.
- Simulation users now number 2,300 per year.
- 359 publications have resulted from NCN-supported research since 2002.

- Since NCN's inception in 2002, nearly 16 percent of NCN publications have been coauthored across multiple engineering disciplines, and nearly 22 percent have been coauthored across engineering and non-engineering disciplines. The number of co-authored publications resulting from NCN-related activities has increased between 2002 and 2005.
- Industrial users have been increasing and accounted for 8 percent of users in 2005.
- Users from outside the U.S. now constitute 45 percent of all simulation tool users.
- The average number of co-authors of NCN publications in 2005 was 4.6, suggesting significant levels of collaboration.
- NCN principal investigators come from eight academic disciplines, led by electrical and computer engineering.
- From 2004 through 2006, 23 degrees were awarded to NCN students, of which 12 were Ph.D.s.
- NCN supported 26 REU students and 53 Summer Undergraduate Research Internship students in 2005.
- Since 2002, NCN PIs have developed 25 new courses.

Although it is tempting to read across these quantitative indicators in an effort to compare the activities studied along some dimension of "performance," the fact is that the four activities are sufficiently different in their specific purpose, structure, funding, date of inception, and requirements that doing so should be undertaken with great care. Moreover, the situation is made even more complex by the data reporting requirements, which differ for each activity. The following paragraphs nonetheless seek to summarize our findings in a primarily qualitative manner, organized around knowledge transfer categories, while avoiding inappropriate comparisons.

Publications, a primary means by which research knowledge is transferred to NSE colleagues and to broader research communities, show substantial rates of production for these four activities. Where time-series data on publications were available or meaningful (i.e., NIRT and NSEC), publication rates have increased annually as individual awards matured. The substantial volume of research output from all four activities is especially remarkable given the time required for newly-formed research teams to plan, organize, conduct research, and get results into print.

Collaborations are a key feature of NSE research and education, an accepted requirement for the frequent and complex interactions among members of the community necessary for advance in the field. The collaborations inferred from the data shown above suggest wide variations in the form and partners involved—e.g., individuals, universities, small firms, and government labs—engaged in co-authoring publications, formal partnering across institutions, sharing equipment, supporting and being supported by each other financially, training and being trained, and interacting via computer-based networks. Industry involvement in these collaborations is a feature of research and education support programs as well as of user facilities, and where data on industry involvement over time are available there is a trend toward increased industry collaboration.

The standard indicators of technology transfer from research organizations, suggesting potential for commercial application, show high levels of activity and impressive totals for those programs collecting such data—NIRT and NSEC. Compared with similar technology transfer data from U.S. research universities, the two programs show a considerably higher rate of invention disclosures per research dollar. Specifically, NIRT and NSEC awards have generated 284 invention disclosures, 30 patents, and 12 licenses thus far. With government investment in NIRT and NSEC at around $170 million, this equals about $0.56 million per invention disclosure, a number well below the average cost of invention disclosures in U.S. research universities.[2] Industry support for NSECs for all years totaled more than $15 million, and NNIN users paid about $16 million in fees for the period March 2005-February 2006. Of this, industry paid more than $5 million, suggesting a pattern of substantial cost savings or levels of investment by industry, adding up to more than $30 million.

Promotion of interdisciplinary research is built into these activities in different ways, but all of them show substantial indication that such activities are widespread, generally surpassing formal program requirements. Each NIRT award represents, on average, participation by researchers from three different departments; in a typical NSEC, researchers come from just over nine different departments. Although not necessarily indicating actual integration of knowledge across fields, users of the NNIN are spread among 11 fields of science and engineering; and the 31 principal investigators of NCN, while somewhat concentrated in electrical and computer engineering, are drawn from more than seven broad disciplines.

NIRT and NSEC awards are contributing significantly to the technical workforce by supporting graduate research and training, and providing undergraduates with valuable team-based research experience. They also have produced numerous new courses and several new degree programs. NNIN's educational portal is the focus for the network's offerings of training materials, lesson plans, and activities produced by individual sites. The Website also provides lectures on nanotechnology, discipline-specific discussions at the graduate level, lectures on mentoring, and instructional material on social and ethical considerations in nanotechnology. NCN, working through its NanoHUB, disseminates products of the National Center for Learning and Teaching in NSE. Workshops and short courses are commonly used for interacting with industry by all of the activities.

Finally, each activity addresses to some degree the environmental, health and safety, and societal and ethical implications of NSE. New users of the NNIN, for example, receive extensive training prior to the use of facilities, totaling 6,700 hours of training for new users from March 2005-February 2006. Each of the four nodes of the NSEC Center for Nanotechnology and Society devotes attention to different aspects of the societal and ethical implications of NSE.

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[2] A FY 2004 survey conducted by the Association of University Technology Managers reported that the average output was four invention disclosures for every 10 million dollars in research expenditures ($2.5 million per invention disclosure); the average output was 2.55 patent applications for every 10 million dollars in research expenditures ($4 million per patent application); and the average output was about one start-up company formed for every 100 million in research expenditures ($100 million per start-up).

Overall, the four activities provide overlapping and complementary forms of knowledge transfer to different groups. The NIRTs and NSECs emphasize research involvement and education of undergraduates and graduate students, using more traditional methods of knowledge transfer: classroom learning and laboratory experience under the guidance of mentors. The infrastructure support awards have different primary audiences, appropriate to the resources available to each. NCN offers access to unique resources for academic and industrial users, with support from and interaction with the staff at each network site providing considerable transfer of knowledge and know-how. Workshops, seminars and short courses are key mechanisms of transfer for both NCN and NNIN. Both awards emphasize outreach to the public, K-12 students, and teachers, complementing the awards programs' relative emphasis on students and researchers in higher education settings.

I. Introduction

This report presents findings of an assessment of knowledge transfer activities within four activities funded by the National Science Foundation. It documents the partnership and knowledge transfer and innovation activities related to two Nanoscale Science and Engineering (NSE) research and education programs and to two nanoscale user facility awards. The two research and education support programs studied are:

- The Nanoscale Interdisciplinary Research Teams (NIRT)
- The Nanoscale Science and Engineering Centers (NSEC).

The two user facility awards studied are:

- The National Nanotechnology Infrastructure Network (NINN)
- The Network for Computational Nanotechnology (NCN).

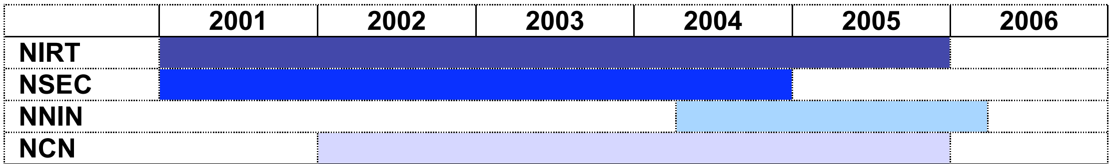
These activities are to some extent experimental because they are intended to meet the needs of the unusual and dynamic scientific and engineering research, education, and other activities characteristic of NSE. It is important to assess how well these activities are accomplishing their goals, not just *post hoc* but as they are unfolding so that changes might be made to improve their operation, if needed. Exhibit I-1 provides brief descriptions of the activities assessed in this study.

Exhibit I-1: Programs and Networks Assessed in this Study

			Description
Programs	NIRT	Nanoscale Interdisciplinary Research Teams	This program encourages team approaches to address research and education themes where a synergistic blend of expertise is needed to make significant contributions. The Nanoscale Interdisciplinary Research Teams activity supports small collaborative groups led by three to five Principal Investigators.
Programs	NSEC	Nanoscale Science and Engineering Centers	Centers bring together researchers with diverse expertise—in partnership with other private and public sector organizations—to address challenges and opportunities that are too complex, and multi-faceted for individual researchers or small teams to tackle in shorter periods of time. They integrate research with education both internally and through a variety of partnership activities ranging from K-12, undergraduate, graduate, to post-doc level, as well as general public. Each NSEC, whether based at a single institution or distributed across a number of institutions, must have an overarching research and education theme, well-integrated programs, and a coherent and effective management plan. The NSECS as a whole span the range from exploratory research—focused on discovery—to technology innovation, and involve a broad spectrum of disciplines such as engineering, mathematics and computer science, the physical, biological, environmental, social and behavioral sciences, and the humanities.
Networks	NNIN	National Nanotechnology Infrastructure Network	This network provides infrastructure for research: on-site and remote access for users, from academia, small and large industry, and government, to advanced top-down patterning and processing and bottom-up synthesis and self-assembly, development of tools and techniques, and comprehensive web and computation infrastructure in support of nanotechnology. The facilities comprising this network are diverse both in capabilities and research areas served as well as in geographic locations, and the network has the flexibility to grow or reconfigure as needs arise. The NNIN broadly supports nanotechnology activities outlined in the National Nanotechnology Initiative investment strategy. It provides users across the nation access to leading-edge fabrication and characterization tools and instruments in support of nanoscale science and engineering research, develop and maintain advanced research infrastructure, contribute to the education and training of a new workforce skilled in nanotechnology and the latest laboratory techniques, conduct outreach to the science and engineering communities, and explore the social and ethical implications of nanotechnology.
Networks	NCN	Network for Computational Nanotechnology	This program catalyzes the formation of teams of theorists, computational scientists, and experimentalists in research that addresses key challenges in realizing integrated nanosystems; supports the research and the broader National Nanotechnology Initiative with an infrastructure that provides ready access to high-perfomence computing and visualization; facilities collaboration, delivers simulation services, and enables solutions to large, multi-scale problems by assembling standard, open-source components tht are available to the entire community; and develops educational packages that can be incorporated into the curricula to train students, scientists, and engineers. The NCN addresses three research themes: (1) nanoelectronics, (2) nanoelctromechanics, and (3) nanobioelectronics.

These two programs and two network awards represent about one-third of the budget for the NSF Nanoscale Science and Engineering priority area, which has been funded since FY 2001 and is currently operating at about $338 million for FY 2006. The goals of NSE are to "support fundamental knowledge creation across disciplinary concepts and tools at the nanoscale, and to catalyze synergistic science and engineering research and education in emerging areas of nanoscale science and technology."[3] They have been in operation for different lengths of time, and our evaluation and assessment covers different time-frames, as illustrated in Exhibit I-2.

Exhibit I-2: Years Covered by this Report



Because of its key role in the creation and growth of the nanoscience and nanoengineering research community, NSF seeks to invest in the knowledge transfer processes involved. Knowledge transfer is the deliberate process of exchanging information from one part of the knowledge system useful to another part, often across sectors or disciplines. When such comparisons are valid, the results of these programs and awards will be compared with other programs both within NNI as well as in other fields using similar strategies, e.g., interdisciplinary centers, user facilities, and networks (if indeed there are comparators for the latter). Knowledge transfer is essential for the advancement of scientific and engineering activities. This is perhaps more true for NSE than for other parts of research and development because of the inherently interdisciplinary and transformative nature of NSE. NSE research and development draws from diverse fields such as physics, materials sciences, chemistry, and electronics research and is expected to flow into hundreds of fields over the next decade. Ensuring knowledge flows and transfer among NSE researchers and centers--particularly where it would involve research disciplines that are not accustomed to working together--is central to advancement. This report focuses on measuring these transfer processes and their outputs.

The report is organized to facilitate analysis of all four activities in comparison with each other and with other governmental activities. Following this introduction, Section II describes the features that distinguish the four NSE activities from other research and education support programs. Section III presents an overview of activity and output indicators used to document and assess knowledge transfers in the four activities. Sections IV-VII present detailed data about each of the activities, their knowledge transfer activities and their outputs, as stand-alone reports. Appendix A places the NSF's NSE activities studied in the larger context of the National Nanotechnology Initiative (NNI). Detailed data tables that support the results presented for the four activities are available in electronic form from SRI and the National Science Foundation.

Each of the four activities is designed to address specific needs associated with nanoscience and engineering research. They are designed to be complementary, at least to some extent, and they are designed to address a specific need for public support to basic and applied research in the diverse fields covered under the broad heading of NSE.

[3] NSF Program Solicitation NSF 04-043, Nanoscale Science and Engineering (NSE), p. 2.

II. Distinguishing Features of NSE Activities within the NNI

The NSF activities that are the focus of this report are experimental in their design in large part due to the unusual features associated with nanoscale science and engineering research. These features include the specialized equipment needed, the creation and use of specialized materials, the interdisciplinary nature of the research as well as the need for interdisciplinary interpretation and use of the results, the potential for applications that could have economic impacts, the need for specialized education and training across a number of fields, and the need for collaboration among individuals and institutions. Each of these is discussed below as it relates to the four NSF activities.

Specialized Equipment and Infrastructure

Nanoscale science and engineering research requires specialized equipment. NSF activities intended to address this need are designed to link researchers with research infrastructure and resources, even when they are geographically distant. The equipment is expensive and therefore is not found in many research laboratories. Experiments use advanced top-down patterning and processing and bottom-up synthesis and self-assembly, development of tools and techniques, and comprehensive Web and computation infrastructure in support of nanotechnology. Special microscopes such as scanning tunneling microscopes and atomic force microscopes make it possible to conduct experiments and view the results. Special simulation services are often needed to understand what is happening at the atomic scale under different conditions. Special equipment to change material properties (such as temperature) is also needed. In other cases, synchrotrons can also help NSE research.

Materials

Highly specialized materials, materials handling, substrates, and platforms are needed to perform many of the leading-edge NSE experiments. NSF programs are playing a role in providing access to these materials through direct contact or through network exchange of data and virtual access. This is particularly true of the networks, which are designed to ensure that many different groups can learn about and gain access to specialized equipment and computational resources.

Interdisciplinarity

Research into the features of materials at the nanoscale is characterized by the broad mix of disciplines needed to craft experiments and to understand the outcomes. Much of the research requires very highly specialized equipment and know-how to make experiments workable. Chemists, physicists, and materials scientists are often working together in nanoscience or engineering experiments. Increasingly, biologists and biochemists are involved as well, since biological materials will be involved.

The centers, programs and networks that are part of the NNI broadly, and specifically a part of NSE, were created because NSE research requires a mix of disciplines, theoretical approaches, and engineering capabilities. Rarely are these functions available within the same person, and equally rarely are they available in the same geographic or organizational location. Thus the centers and networks supported by NSE activities are designed to encourage researchers from a wide range of traditional departments and disciplines to collaborate. This adds to the dynamism of the research, but also makes it a challenge to manage, monitor, and track research outputs and outcomes.

Time-line Between Basic Research and Economic Applications

NSF research programs and networks are not designed to have specific commercial applications. Even so, many researchers working on fundamental research questions are well aware of the potential applications of their work. In addition, many researchers from corporate research labs seek out the ideas and collaborative energies of counterparts in academic and government laboratories. A number of nanotechnology applications already have reached the marketplace, and there is sufficient interest in the potential for application that academic-industrial collaboration is encouraged. NSE activities are open to industrial partnerships in cases where this might bear fruit. Industry researchers bring dynamism in and of themselves. Their participation can also be an indicator of the potential for commercializing particular lines of research.

Education and Training

The nanotechnology revolution has barely begun, and a new generation of researchers is being trained now in labs funded by NSF as well as by other government agencies. This is a critical phase of the development of NSE and an important role for the NSF. As participants in research activities, students and researchers alike are being trained as an integral part of the NSF research, education, and infrastructure awards. It can be difficult to decouple the activities because so much of advanced training takes place in a hands-on manner in these laboratories. That said, all four of the activities included in this study have important roles to play in education and workforce training.

Collaboration

Each of the above features of NSE research, education, and application requires extensive collaboration by participating individuals and institutions. Although collaboration increasingly has been recognized as a key ingredient in advancing research in all fields, it is especially important for NSE. For each of the above requirements, collaboration is essential for at least three important reasons: first, the cross-fertilization of ideas, modes of thought, concepts, data, and methods from multiple technical fields is important for advances in NSE.[4] Although collaboration does not ensure that the *integration* of knowledge essential to interdisciplinary research occurs, it is often a necessary if not sufficient condition. Second, the unique requirements for specialized and expensive equipment means that resources must be shared, researchers must have easy and relatively inexpensive access to resources, and the means for

[4] Note, for example, the awarding of a $40 million, 15-year project to the National Academies to facilitate interdisciplinary research and teaching (the Keck *Futures Initiative*), and the initiation of the NIH Roadmap, both of which were based on the increasing view among scientists that significant breakthroughs are more likely to occur at the interstices of the traditional disciplines.

accomplishing such sharing must be carefully developed and maintained with the users in mind. Again, collaboration is necessary if not sufficient for this to occur. Finally, the potential societal benefits from NSE research cannot be realized without close cooperation and involvement of several sectors of our society: research institutions, industry, and institutional guardians of public safety and health. Collaborations among all of these are thus an important ingredient in achieving the social advances that NSE research promises.

III. Indicators of Knowledge Transfer Activities and Outputs

Knowledge Transfer and Impact Indicators: Definitions and Limitations

Earlier in this report we defined knowledge transfer as the deliberate process of exchanging information from one part of the knowledge system to other parts, often across sectors or disciplines. The four activities we focus on in this report play different but intentionally overlapping and complementary roles in achieving the knowledge generation, transfer, and use goals for which they were designed. To describe the knowledge transfer processes and outputs of the four activities, it is necessary to identify appropriate indicators that capture the unique features of NSE programs just outlined in the previous section. In particular, based on discussions with NSF, SRI identified six priority categories of nano program knowledge transfer activity and output that are particularly important to address in this project. These categories, in the order in which results are presented in this section of the report, are:

- Research Outputs
- Collaborations
- Economic Impact
- Interdisciplinarity
- Education and Training
- Societal, Ethical, Environmental, Health and Safety Implications

We begin by defining each of these categories; we then present the indicators we have selected for documenting the knowledge transfer activities and outputs of each of the four activities studied. It is important to realize that results presented here must be carefully considered by taking into account two limitations. The first relates to limitations of the data available to us, given the resources committed to the study. Specifically, data sources included those submitted by NSF principal investigators (PIs) as part of the regular NSF reporting requirements for awards; publicly available, supplemental data available on institution and organization Websites; annual and final reports prepared for NSF by awardees; and responses to SRI's requests to PIs for additional information about specific topics. In many instances the data were missing, incomplete, or internally inconsistent, limiting our ability to address several aspects of the activities and impacts that will be desirable to include in further work of this kind.

The second limitation has to do with the complexity of the phenomena that we sought to measure: processes and, especially, ouputs that are in themselves multidimensional and, under the best of circumstances, defy simple measures. Thus, where possible, we relied upon multiple indicators of these processes and outputs, as many as the available data allowed and that stood the test of face validity. The indicators are imperfect and partial, each in different ways, and that must be taken into account in interpreting our results. We have attempted to identify, for each of the four activities, how the indicators selected are limited in their ability to capture the full scope and complexity of each category of ouput. First we offer brief definitions of each process/output category, reflecting the relevant comments about each made in the previous section dealing with the demanding requirements for advances in NSE. It is by no means coincidental that our categories bear a close relationship to these requirements.

Research Outputs. Research is intended to advance knowledge, so the outputs from research activities consist fundamentally of new knowledge. The most common indicators of knowledge output involve counts of the varieties of ways in which the content of knowledge is transferred from those who generate it to other members of the research community. These include journal publications, conference proceedings, symposia, trade journals, and, increasingly, in digital form on the Web. In the case of research infrastructures such as networks, results occur as researchers gain access to facilities and other resources essential for achieving advances. Thus measures of facilities use may also serve as indicators of research activity and knowledge flow.

Collaborations. These are formal or informal interactions involving multiple contributors (which could be individuals, teams, organizations, or governments) who provide time, money, facilities, knowledge, or other resources to achieve mutually desirable research goals. Such collaborations often take the form of formal partnerships or other agreements to work together under specified conditions. Often collaborations involve physical interaction, but increasingly they can be done successfully at a distance using information technology.

Economic Impact. Usually this is defined as increased economic value of individuals, organizations, regions or other entities. When research is the driving force, economic impact may be a long-term outcome, so that intermediate measures generally recognized as indicators of the potential for economic development are often used. Examples of such intermediate output indicators include counts of invention disclosures, patents and patent applications, licenses, and spin-off companies representing efforts to commercialize research results.

Interdisciplinarity. We accept the National Academies definition of interdisciplinary research, which requires the *integration* of knowledge, methods, and/or data from more than one established field of inquiry. With this definition, interdisciplinarity can occur within single researchers as well as within groups, and physical collaboration or co-authorship of publications does not necessarily involve the actual integration of knowledge—like the distinction between a patchwork quilt (multidisciplinary) and a seamless blanket (interdisciplinary). Nevertheless, commonly used indicators of interdisciplinarity include co-authorship across disciplines of publications, identification of the departmental affiliations of collaborating researchers, and bibliometric measures such as the range of subject categories of citations appearing in published work.

Education and Training. This category of processes and outputs includes formal classroom learning, learning-by-doing, experiential learning, and self-improvement through access to appropriate resources. It also includes know-how obtained through working with materials, devices, and processes, such as the user training involved in network awards. Output measures used include counts of graduates by degree, workshops and training programs held, and participation in formal education outreach programs such as Research Experiences for Undergraduates (REU).

Societal, Ethical, Environmental, Health and Safety Implications. Here we relied upon the definitions used by NNI for these terms in the context of NSE programs:

> **Environmental, Health and Safety.** This category of outputs includes research results that (1) significantly increase fundamental understanding of nanoscale material interactions at the molecular and cellular level through *in vitro* and *in vivo* experiments and models; (2) significantly increase fundamental understanding of nanoscale materials interactions with the environment; (3) significantly increase understanding of the fate, transport, and transformation of nanoscale materials in the environment and their life cycles; or (4) identify and characterize potential exposure, determine possible human health impact, and develop appropriate methods of controlling exposure when working with nanoscale materials.
>
> **Ethical and Societal Issues.** This category of outputs includes results of research and other activities that (1) foster and encourage forums for dialog with the public and other stakeholders; (2) create and distribute new informational materials about nanoscience and nanotechnology to better communicate with the broad public; (3) identify and assess education and workforce development needs in nanotechnology development; (4) identify and assess barriers to the adoption of nanotechnology in commerce, healthcare, or environmental protection; or (5) identify and assess significant ethical issues in the selection of research priorities and applications in nanotechnology.

Exhibit III-1 presents the specific indicators we used to measure knowledge transfer activities and impacts as just defined, chosen to accommodate the available data and requirements for acceptable validity. The limitations of each of these indicators within the context of individual programs will be discussed as the results of our analyses are presented in the following sections of the report.

Exhibit III-1: Indicators of Knowledge Transfer Activities and Outputs by NSF Program

Category	NIRT	NSEC	NCN	NNIN
Research Outputs	Publications	Publications	Publications simulation tools Software	Publications
Collaborations	Organizational partners (academic institutions, non-profits, industrial or commercial firms, state or local governments, schools or schools systems)[5] Individual collaborators	Institutional partners (research universities, female and minority serving institutions, industry, museums, K-12 schools, international partners, national labs)[6]	Institutional affiliation of PIs Institutional affiliation of co-authors of publications (network institutions, other universities, industry, federal government, foreign) Network users by type, institutional affiliation and country	Institutional affiliation of users and of new users (local site academic, other university, large company, small company, State & Federal government, 2-year college, 4-year college, pre-college, foreign) Co-authored publications
Economic Impact	Inventions disclosed Patent applications Patents awarded Licenses issued Spin-off companies	Inventions disclosed Patent applications Patents awarded Licenses issued Spin-off companies Industry support	Patents Spin-off companies Estimated cost savings to users (from industry and other non-network organizations)	Start-up companies User fees Industry use (large companies, small companies)
Interdisciplinarity	Departmental affiliations of co-PIs on award	Departmental affiliations of faculty-level participants	Departmental affiliations of co-authored publications Departmental affiliations of PIs Network users by field	Network users by field
Education and Training	Number of post-docs Number of students participating Number of graduates by degree Graduates hired by type institution Contributions to curricula	Degrees awarded REU participants RET participants New courses, curricula Seminars, workshops, short courses, colloquia	Workshops and training programs conducted Degrees awarded Students supported REU participants SURI participants Courses, seminars, workshops	REU participants RET participants New users trained Graduate students participating in research PhDs awarded Workshops, short courses
Societal, Ethical, Environmental, Health and Safety	Examples provided in annual reports and by PIs	Examples provided in annual reports and by PIs	Examples provided in annual report and by PIs	Examples given in annual reports Hours of training in lab safety and health Number of users receiving training in lab safety and health

[5] These examples are from NSF's Fastlane reporting guidelines for annual reports.
[6] These categories are based on the NSF official document: *Guidelines for NSEC Continuation Requests.*

IV. Nanoscale Interdisciplinary Research Teams (NIRT)

Key Findings-NIRT

- Since the program was initiated in FY 2001 and through FY 2004, all NIRT awards have produced a cumulative total of 1,086 publications in refereed technical journals.
- Typical NIRT awards increased their publication output each year; the 44 FY 2001 awardees report an average output of 26 publications per award in FY 2004, the year they filed their final reports.
- During FY 2001-FY 2004, both the total number of organizational partners per year and the number of individual collaborators per award increased over time; for the FY 2001 cohort of awards, the number of partners increased from 42 to 71 and the number of partners per award increased from 1.3 to 3.4.
- During FY 2001-FY 2004, 31 percent of awards reported some form of technology transfer output: invention disclosures (109), patents filed (87) and patents awarded (9).
- 11 spin-off companies emerged from NIRT awards during FY 2001-FY 2004.
- For FY 2001-FY 2004, the average number of departments represented on awards was 2.75, indicating interdisciplinary coordination.
- During the same period, 459 degrees were granted as a result of NIRT activities: B.A.s (135), M.A.s (128), and Ph.D.s (195).
- During FY 2001-FY 2004, nearly 50 percent of NIRT awards contributed to curriculum development.

Introduction

One of the mechanisms funded under this initiative was the newly-created category of Nanoscience Interdisciplinary Research Teams (NIRT). Since research and education areas in nanoscale science and engineering are inherently interdisciplinary, by requiring for each proposal at least three co-PIs, the NIRT Program encourages team approaches where a synergistic blend of expertise is needed to make significant contributions. Each of the NIRT competitions solicited proposals in several specified thematic areas, ranging, for example, from nanoscale devices and system architecture to nanoscale processes in the environment.

More specifically, the NIRT Program supports small collaborative groups of three to five principal investigators (at the faculty level or equivalent) working on one of the specific research or education themes. In addition to their research activities, the awards are aimed at the development of a skilled workforce and an informed public. NIRT teams are encouraged to pursue partnerships with industry and government labs. The award size per project is normally $250,000 to $500,000 per year, for up to four years.

NIRT funding began in FY 2001, when a total of 44 grants were awarded. Funding continued through FY 2005, with a total of 259 grants having been awarded over the five year period. SRI analyzed a total of 210 NIRTs awarded during FY 2001-04; those from FY 2005 were not included because at the time of the analysis it was too soon to expect much in the way of reported outputs.

The indicators shown below were tabulated from annual and final reports to NSF, and confirmed by PIs. Exhibit IV-1 shows the percentage of awards for which SRI tabulated results.

Exhibit IV-1: Percentage of Awards for which SRI Tabulated Results

Fiscal Year	Awardees Tabulated	Total Awardees	Percent Tabulated
2001	41	44	93%
2002	51	54	94%
2003	52	61	85%
2004	45	51	88%
Total	189	210	90%

Source: 2001-2006 PI Annual Reports to NSF

Indicators Tabulated[7]

The following indicators were tabulated by SRI:

Publications Resulting From NIRT Support

- In Peer-Reviewed Technical Journals
- In Peer-Reviewed Conference Proceedings
- In Trade Journals
- With Multiple Authors: Industry
- With Multiple Authors: Co-Authored with NIRT Faculty
- Total Journal Publications

NIRT Technology Transfer

- Inventions Disclosed
- Patents Filed
- Patents Awarded
- Licenses Issued
- Spin-off Companies Started

Degrees to NIRT Students

- Bachelor's Degrees Granted
- Master's Degrees Granted
- Doctoral Degrees Granted

[7] The complete data on which the results reported here are available in electronic form from SRI and the National Science Foundation.

NIRT Graduates Hired (by)

- Industry
- Government
- Academic Institutions

NIRT Collaborations

- Organizational Partners
- Individuals

NIRT Influence on Curriculum

- Contributions to Curricula

NIRT Information Dissemination/Educational Outreach

- Workshops, Short Courses to Industry
- Workshops, Short Courses to Others

We were able to tabulate data from 189 of the 210 awards, and data from 87 of these were confirmed or corrected by the PIs. Here are the responses categorized by Research Theme:

Exhibit IV-2: NIRT Response by Research Theme

Research Theme	Awardees Tabulated
Structures and Phenomena	73
Devices and Systems	38
Manufacturing	29
Biosystems	19
Theory, Modeling and Simulation	17
Environment	10
Societal and Educational Impact	3

Source: NSF NSE Program, 2005

To understand how the activities and outputs of a typical NIRT award "unfold" over time, SRI undertook a time series analysis of all NIRT awards from the first year of the program (FY 2001) through their completion. (While we did not do the same for later cohorts, there was no major change that would lead us to believe that later cohorts would show different patterns). The analysis was created by tabulating available data from annual and final reports from all 44 NIRT awards made that year, through all four years[8] of their existence, and exploring selected categories of interest (e.g., publications, collaborations). Not all awardees submitted reports consistently; of the 44 awards in the cohort the largest number of reports available in any year was 32, and only 14 NIRTs reported across all years. The resulting charts and tables (Exhibits IV-4, IV-6, IV-7, IV-12, and IV-13) show, for each award year, the number of reports available

[8] In a few cases, NIRT PIs filed a report that appeared to be for all or part of a fifth year. These showed very few differences from the fourth year report (usually one or two articles that had moved from "accepted" status to "published"). Rather than create a misleading "fifth project year" based on a scant number of records, we substituted "fifth year" reports for final fourth year reports when the latter was missing or both were present.

(N), the total item count for all reporting NIRTs, and the average number per NIRT. For example, in year one, 32 NIRTs filed annual reports showing a total of 44 post-doctoral researchers, for an average of 1.4 per award. As with other tables in this time series, the fourth year shows an apparent decline in the total from the third year, but that is an artifact of the smaller number of reports filed in the fourth year--in this case, the average per award is slightly higher.

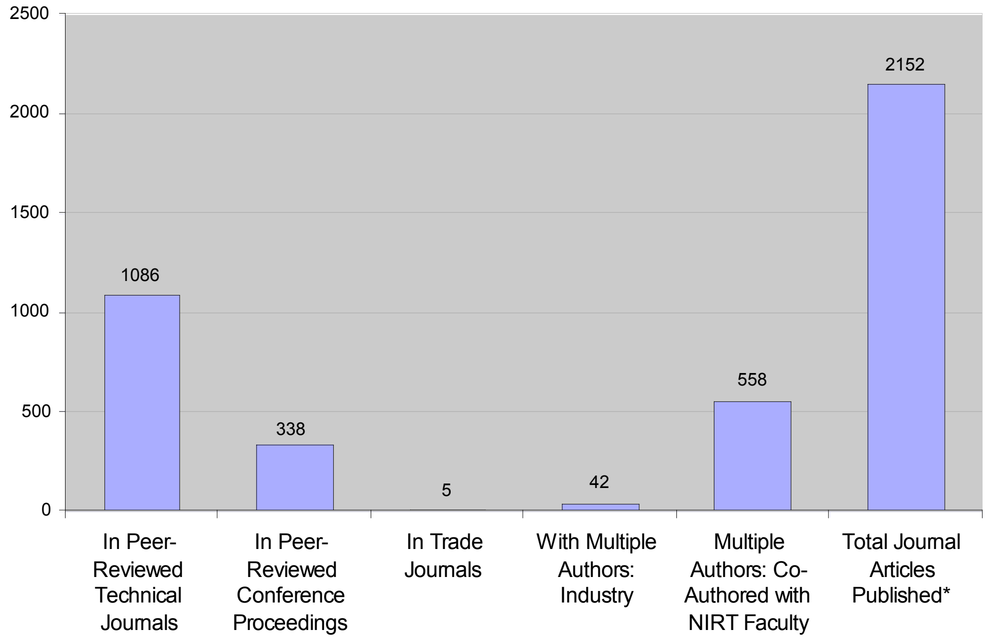
While we were unable to find comparable output figures for NSF's individual-investigator and small group research awards generally, we observe that in most cases the number of NIRT products is markedly higher than common experience with ordinary awards of the former type would suggest. One contributing factor may be the award design (collaborating PIs). All NIRTs through FY 2005 averaged 4.27 PIs per award. Another factor is likely to be the larger NIRT funding level. According to the Director's Merit Review report to the National Science Board for FY 2001 (NSB02-21) the average annualized amount for individual investigator and small group research grants awarded in that year was $113,601. The average annualized NIRT award size in FY 2001 was about $325,000. Thus the average annualized NIRT amount is about 2.5 times that for the average "individual" research grant. Also, most data were reported cumulatively, e.g., once the name of a graduate student or individual partner was listed in an annual report it appeared in successive reports. Thus we were not able to determine "turnover" among students or partners.

Research Outputs

Exhibit IV-3 demonstrates the total outputs of publications reported:

Exhibit IV-3:

Publications Resulted from NIRT Support, by Type of Publication



Source: 2001-2006 PI Annual Reports to NSF

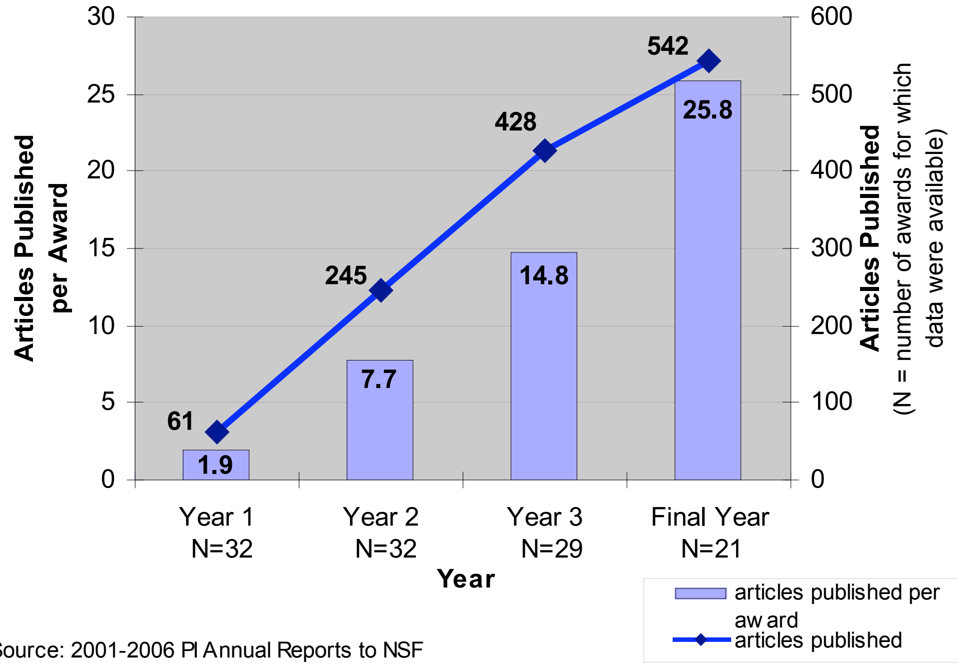
*Note: Total Journal Articles Published do not include Conference Proceedings, and not journal articles are broken down by category.

No data in NIRT annual and final reports indicate the institutional or departmental affiliation of the authors/co-authors, although if desired the author/title listings could be used as the first step for bibliometric and networking analyses.

By the final (fourth) year of their existence, FY 2001 NIRT cohort awards produced an average of almost 26 total published journal articles. Again, this seemingly high number is likely attributable to the number of senior investigators, especially the multiple co-PIs, involved in NIRT awards. Although the annual reports do not indicate the institutional or departmental affiliation of publication co-authors, a bibliometric analysis of NIRT publications output would provide some indication of the interdisciplinarity involved.

Exhibit IV-4:

Articles Published by FY 2001 NIRT Awards, Total and Per Award, by Award Year



Source: 2001-2006 PI Annual Reports to NSF

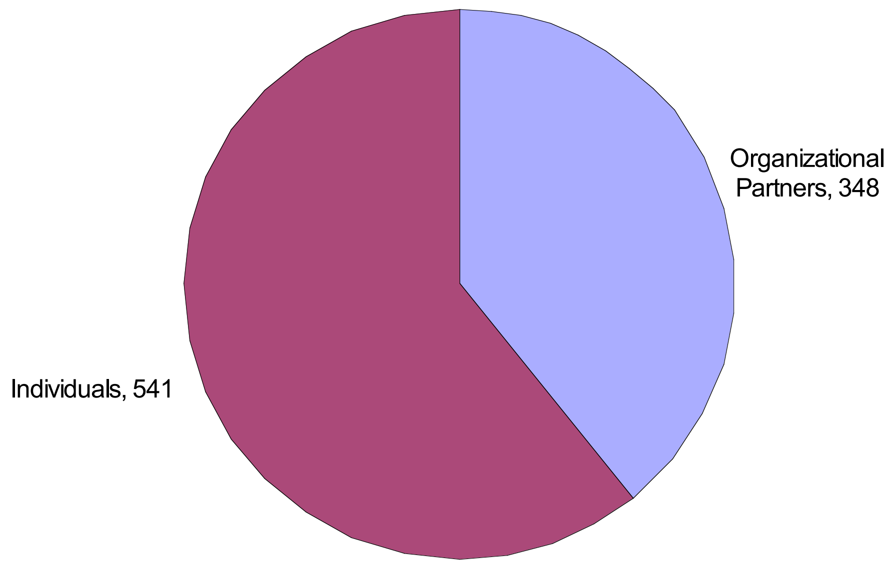
Collaboration

Collaborations were expected to be an integral part of the NIRT Program, as the NSF solicitation requires between three and five senior investigators. Beyond this, though, NIRT PIs were encouraged to form synergistic collaborations with industry, government laboratories, and foreign organizations where appropriate. In particular, NSF encouraged PIs to use the GOALI mechanism (Grant Opportunities for Academic Liaison with Industry, NSF 98-142, http://www.nsf.gov/goali) as a vehicle for collaboration with industry.

Overall, 152 of the tabulated NIRTs (80.4 percent) reported at least one collaboration either with an individual or an organization, with a total of 889 collaborations reported, as shown in the Exhibit IV-5. Among the NIRTs reporting at least one collaboration, each award had on average 2.29 organizational partners and 3.56 individual collaborators.

Exhibit IV-5:

Number of NIRT Collaborations, by Type



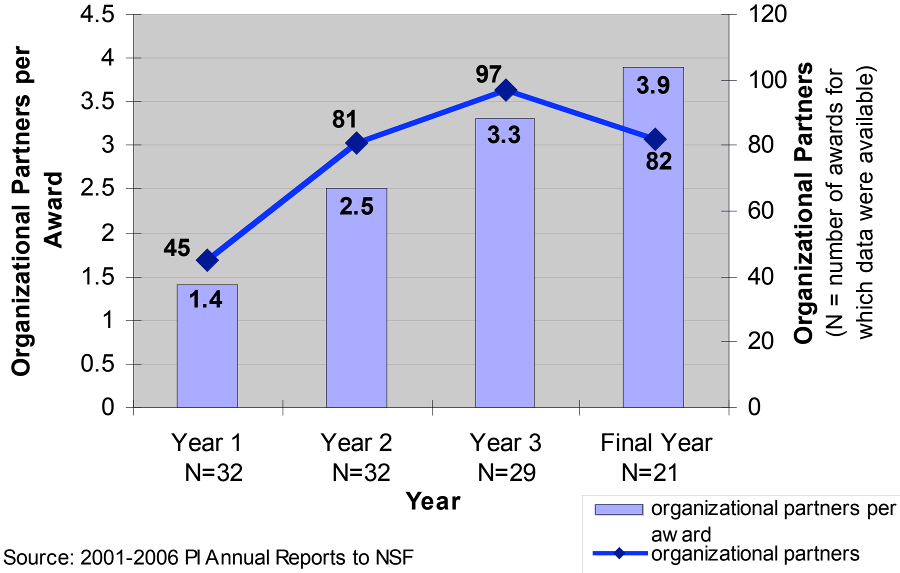
Source: 2001-2006 PI Annual Reports to NSF

As shown in Exhibit IV-6, FY 2001 NIRT awards averaged almost four organizational partners[9] by the final year. This number is probably influenced again by the fact that each NIRT had at least three co-PIs, each of whom may have contacts at different organizations, as compared with a single PI award. Typical organizational partners are industrial firms and other academic institutions. Although partnering organizations are named in the reports, any more detailed categorization such as by organization type or business size would require additional research, particularly where little-known companies are involved.

[9] As defined in Fastlane reporting requirements: A partner organization is one that is outside your own organization. Partner organizations could be academic institutions, nonprofits, industrial or commercial firms, state or local governments, schools or school systems, or other organizations.

Exhibit IV-6:

Organizational Partners in FY 2001 NIRT Awards, Total and Per Award, by Award Year

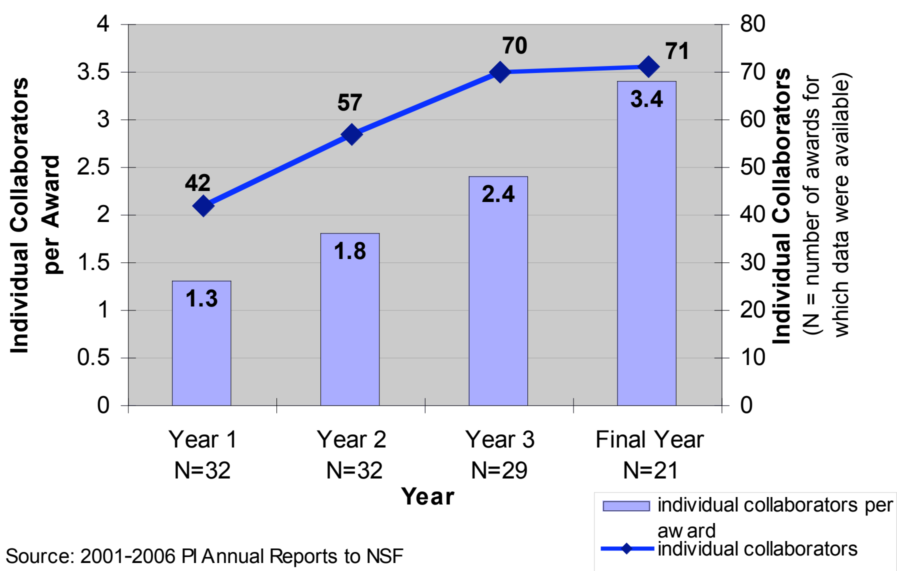


Source: 2001-2006 PI Annual Reports to NSF

As with the organizational collaborations, similar patterns are seen in the tabulation of individual collaborators (Exhibit IV-7), where the average number per award increased steadily from year to year. Individual collaborators are typically faculty members from other academic institutions who provided consultative input to and/or active involvement in the research project.

Exhibit IV-7:

Individual Collaborators in FY 2001 NIRT Awards, Total and Per Award, by Award Year



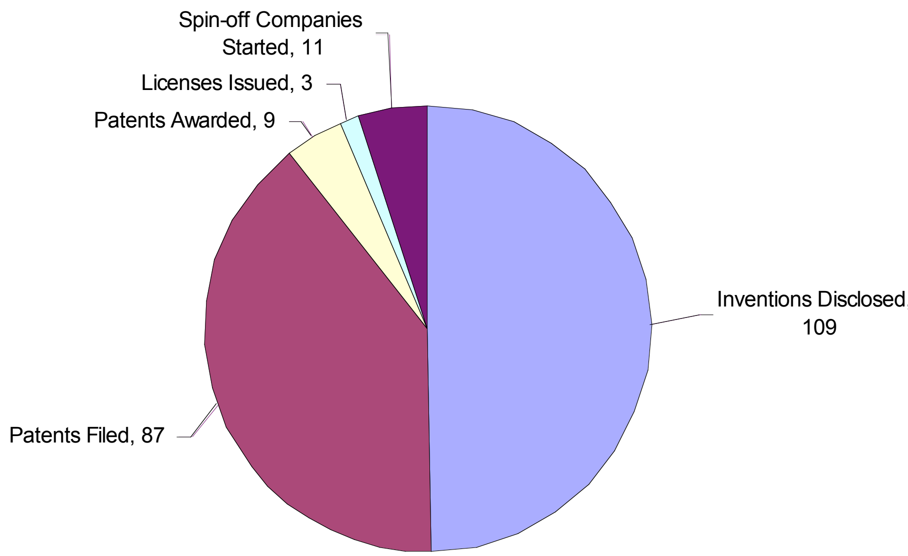
Source: 2001-2006 PI Annual Reports to NSF

Economic Impact

Several indicators of potential economic impact were discerned from NIRT reports. Among the 189 NIRTs, 59 (31.2 percent) reported at least one indicator of potential for technology transfer, such as a license, patent, or spin-off company. Exhibit IV-8 shows the type and number of examples of technology transfer:

Exhibit IV-8:

Number of NIRT Technology Transfer Potential Indicators by Type



Source: 2001-2006 PI Annual Reports to NSF

Several PIs elaborated on some of the economic outputs of the awards:

- One reported work leading to five patents on design of DNA-based nanorobotic devices, a nanomechanical device and related DNA species, as well as the founding of a startup firm, Nanoscience Technologies, that was granted exclusive license to those patents by the New York University Office of Industrial Liaison
- One established collaboration with Illuminex Corp., a small business located in Lancaster, PA, on the development of nanowire photovoltaic devices. Their device fabrication process utilizes nanowire synthesis and processing technology that is an extension of the NIRT research.
- Another was involved in launching the Michigan Institute of NanoTechnology to foster commercialization of nanotechnology products.

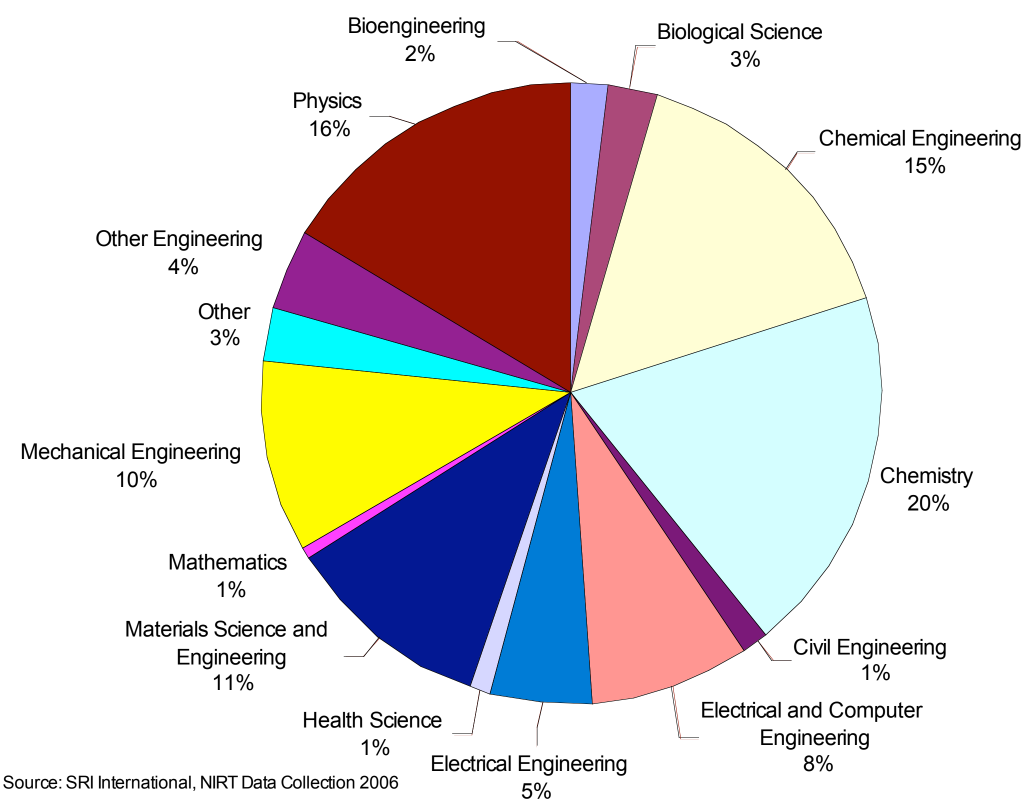
- Each of the PIs in another NIRT award was active in start-up companies or consulting that affected the regional economy. For example, one co-PI founded two companies that provide nanostructures (such as interference gratings) as well as a consulting venture. Another is a board member of a start-up on magnetic memory.

Interdisciplinarity

Due to the basic requirement for multiple PIs, interdisciplinarity is expected in the NIRT Program. One rough indicator of interdisciplinarity is the mix of departments represented among NIRT co-PIs. Exhibit IV-9 shows the departmental affiliation of all PIs involved in the 259 NIRT Program awards (1,106 total PI's):

Exhibit IV-9:

NIRT PIs by Departmental Affiliation



Source: SRI International, NIRT Data Collection 2006

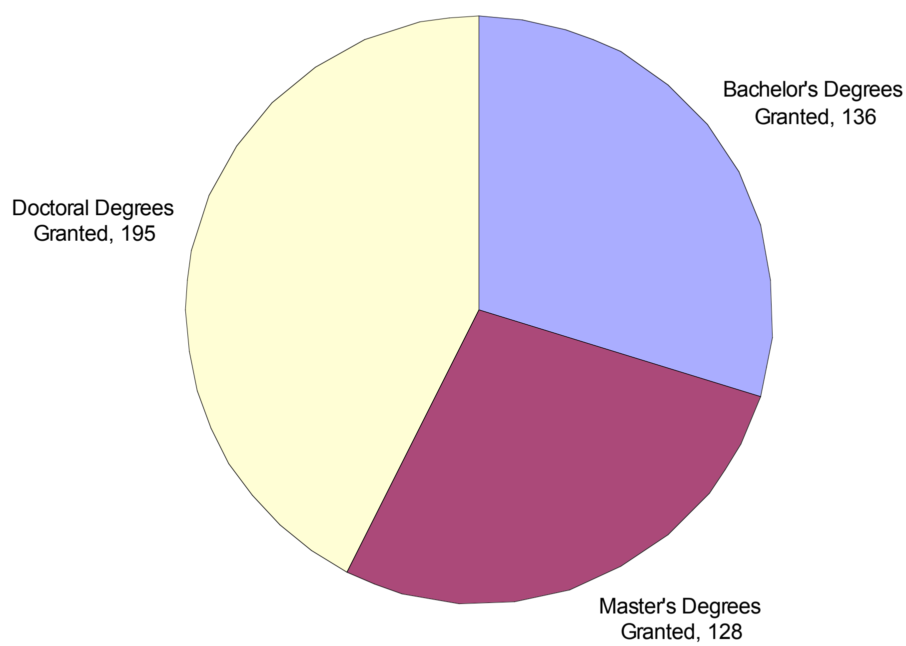
While this gives an idea of the general interdisciplinarity level in the NIRT Program as a whole, it is not necessarily indicative of interdisciplinarity in individual NIRT awards. As mentioned earlier, NIRTs have 4.3 PIs on average. However, the mean number of departments represented in each NIRT is 2.8. That indicates there is some overlap among the departmental affiliations of the PIs on any particular NIRT award. Detailed analysis of award outputs using bibliometric techniques that employ more valid indicators of interdisciplinarity is needed.

Education and Training

Several indicators can be used to document education and training activities in the NIRT Program. These include degrees awarded and students hired by various institutions, as well as contributions to curricula (such as the formation of a new course based on research conducted by the NIRT) and workshops or short courses given to outside individuals. Of the 210 NIRTs awarded between Fiscal Years 2001 and 2004, 85 (45 percent) reported awarding at least one degree, with a total of 459 degrees awarded, as shown in Exhibit IV-10 below:

Exhibit IV-10:

Degrees to NIRT Students, by Degree Type and Number

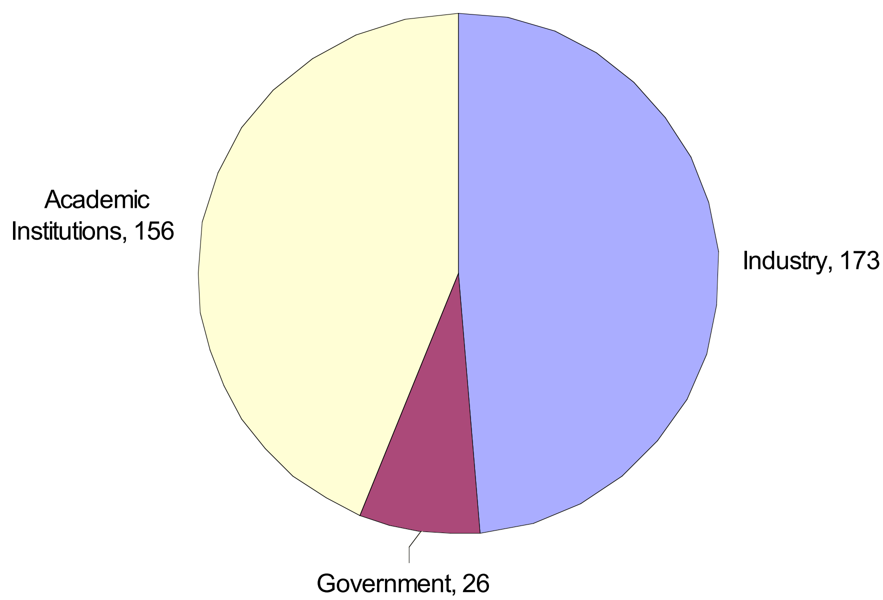


Source: 2001-2006 PI Annual Reports to NSF

80 NIRT awardees (42.3 percent) reported having at least one student hired by another institution; among these 80, a total of 355 students were reported being hired as shown in Exhibit IV-11:

Exhibit IV-11:

NIRT Graduates Hired by Type of Institution and Number



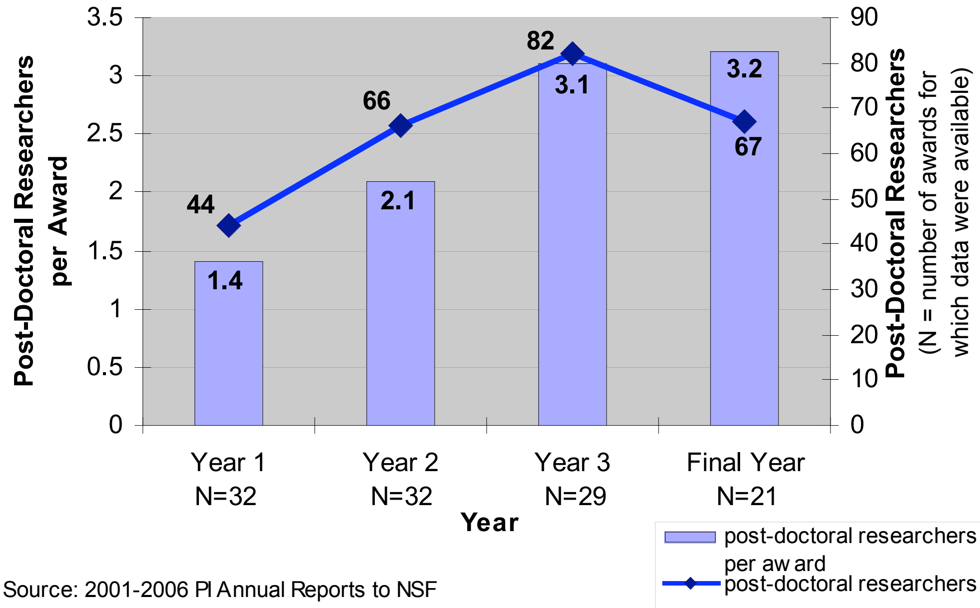
Source: 2001-2006 PI Annual Reports to NSF

Ninety-three NIRTs (49.2 percent) reported at least one contribution to curricula, which usually involved a new course being introduced at their academic institution or in some cases integration of their research into a pre-existing course. A total of 194 contributions were reported, or 2.2 on average among all NIRTs reporting at least one contribution. In addition, 63 NIRTs (33.3 percent) reported giving at least one workshop or short course related to their research. A total of 61 were given to industry, while 178 were given to some other type of audience.

Exhibit IV-12 shows a steadily increasing average number of post-doctoral researchers involved in the FY 2001 NIRT awards until year three, when it levels off. The relatively large number of post-doctoral researchers—an average of more than three per award in the last two award years—may be due to the fact that the NIRT awards involve three to five co-PIs. Further study of departmental affiliations of post-doctoral researchers would shed light on their contribution to the awards' interdisciplinarity, but this information was not available since the reporting requirements for NIRT annual reports do not call for it.

Exhibit IV-12:

Post-Doctoral Researchers in FY 2001 NIRT Awards, Total and Per Award, by Award Year

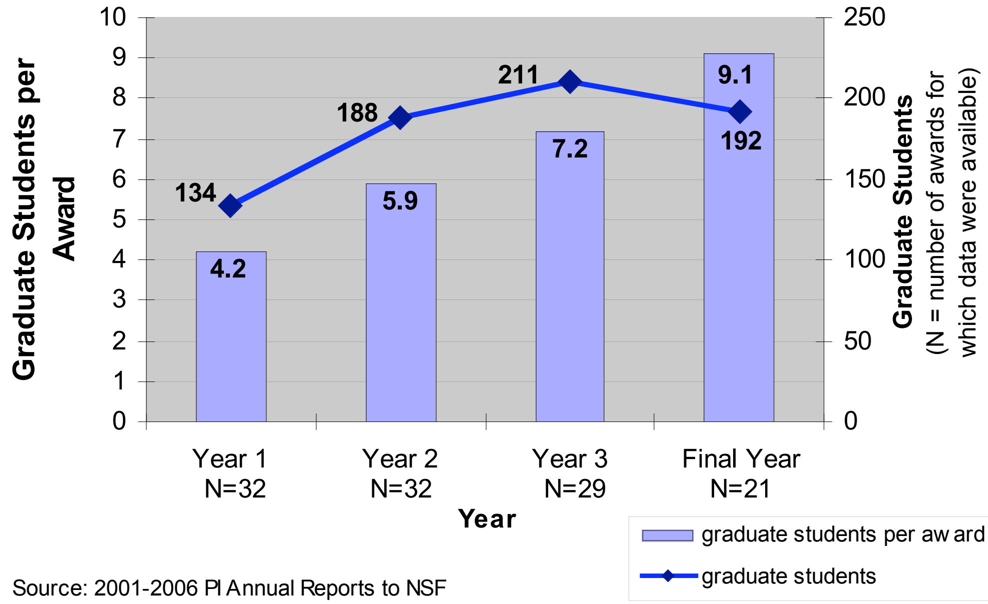


Source: 2001-2006 PI Annual Reports to NSF

Through all four years of the FY 2001 cohort, there is a steady increase in the average number of graduate students per award. As with the post-doctoral researchers and several other cases, the apparently large average number per award (9.1 in the final year) may be due to the fact that several co-PIs are involved. See Exhibit IV-13.

Exhibit IV-13:

Graduate Students in FY 2001 NIRT Awards, Total and Per Award, by Award Year



Source: 2001-2006 PI Annual Reports to NSF

Environmental, Health and Safety Implications

NIRT PIs were asked about possible contributions their research has made to improved environment, health, and safety, and several examples were given, including the following:

- "The tolerance of magnetic nanoparticle uptakes in biological cells in terms of percentage change in the number of cells as a function of concentration of these nanoparticles has been studied experimentally. A critical value of particle volume fraction…was found, which gives the upper limit for safe dosage beyond which the toxicity sets in for the biomedical applications of magnetic nanoparticles."
- "The focus of the research is to modify the material (TiO2) in a way so that it is better suitable for application in the degradation of environmental pollutants. The research points out ways through which ordinary sunlight, particularly the visible portion, could be utilized for environmental cleanup."
- "Surface-enhanced sensors that we developed in part under this award have a promise to be used as biomedical express health-detectors."
- "The work performed on polymer nanocomposites includes the investigation of the nanoscale material properties, polymer-polymer and polymer-filler interactions. Among others, these technologies are being used for design of interfaces in light-weight fuel-efficient automotive applications. The composites interfaces can be tailored to fail at certain strain rates so that the

vehicle impacting an obstacle can absorb significant amount of energy and thus enhance the safety of passengers."

Societal and Ethical Implications

NIRT PIs were asked about possible contributions their research has made in these areas, and several examples were given, including the following:

- "On October 7, 2005, IIT's Center on Nanotechnology and Society hosted a forum which focused on the intersection of nanotechnology, risk and ethics, and human health. In this forum, diverse viewpoints on nanotechnology's impact on society were presented to nanotechnology experts from business, science, law and the social sciences. There will be other events produced by the Center on Nanotechnology and Society at IIT including Nano, Business and Society in the 21st Century, and regulating the future in nanotechnology."

- "Our NIRT team was actively involved with Prof. Rosalyn W. Berne (Virginia) whose NSF-CAREER award was involved with assessments of ethical and societal issues. Those interviews are recounted in her recent book Nanotalk: Conversations with Scientists and Engineers about Ethics, Meaning and Belief in the Development of Nanotechnology. Professor Haglund is pursuing this topic further within the framework of a Templeton Research Lectures award recently made to Vanderbilt by the Metanexus Foundation, on which he is co-principal investigator."

- "In 2005 I participated in a "Citizens' Consensus Conference on Nanotechnology", which brought together a broad cross-section of citizens to engage in a discussion of nanotechnology, along with its potential benefits and risks. In this activity I acted as an "expert panelist" in an open forum with citizens; the citizens summarized their findings and recommendations and presented them, in the form of a written report, to state and local representatives at a press conference held at the Wisconsin Capitol."

In addition to research pertaining to these issues, many respondents reported general outreach activities, including examples such as:

- "As a result of our NIRT-grant, the first in U.S. undergraduate program for BS in nanotechnology was prepared at LaTech's Engineering Department, and it was approved in 2005. Two papers in national press and six papers in local press were published on our project. Project's co-PIs chaired three national symposiums on nanotechnology. Fifteen lectures on nanotechnology were delivered in companies, mostly pharmaceutical and pulp & paper industry (Baxter, EPIC Therapeutics, Ciba Vision, Novartis, nGimat, Cabot, Nanocopoeia; and International Paper Company, Weyerhaeuser, SAPPI Fine Paper, Graphic Package, Smurfit-Stone Mill, Progressive Coating)."

- "Strong international collaborations with Swiss and Israeli partners allow us to spread knowledge and awareness of nanotechnology research worldwide. A strong commitment in dissemination of nanotechnology-based knowledge has been demonstrated through NIRT faculty and student participation in research experiences for undergraduates (REU) and teachers (RET) programs at UIC, Penn and Drexel."
- "We teach a course called the 'Quantum World around Us' to approximately 30 students per year. These are non-science majors, often with humanities backgrounds. The course is now being partnered with a philosophy course as a freshman seminar to discuss issues related between philosophy, science and ethics."
- Our NIRT included forums for discussion of nanoscale topics in a variety of venues:
  1) Visits by co-PI to high school and middle school students through a Chemistry Demo program; Super Science Saturday program.
  2) Developed material for high school teachers on the issue of scale working with a center at the LSU campus, Center for Biomodular Multiscale Systems.
  3) Participated in a LSU program having a high school teacher carry out research in the lab; and develop a nanoscale module for use at the high school level.
  4) Presented a lecture to undergraduate minority students with a focus on nanoscale research (Society of Black Engineers).

V. Nanoscale Science and Engineering Centers (NSEC)

Key Findings-NSEC

- NSEC-related research resulted in 1,822 publications in refereed technical journals over the period 2001-2005.
- In 2005, the 6 NSECs in the first cohort (2001) of awards produced an average of 74 publications per center in peer reviewed technical journals.
- Over 2001-2005, 91 percent of NSEC-related publications were co-authored.
- Most NSEC sites report relationships with more than ten partnering institutions over the reporting period 2001-2005.
- NSEC activities during 2001-2005 resulted in formal technology transfer outputs that included 175 inventions disclosed and 179 patent filings.
- During 2001-2005 258 degrees were granted as a result of research at NSECs: B.A.s (53), M.A.s (57), Ph.D.s (148).
- NSECs offered 862 workshops and short courses during 2001-2005: 123 to industry and 739 to others.
- 149 of the 413 faculty participating in NSECS during 2001-2005 list more than one departmental affiliation.
- Participants in NSECs during this period were drawn from ten different departments, led by Chemistry and Chemical Engineering.
- 17 spin-off companies emerged from NSEC-related activities during 2001-2005.
- Industry support totaled $15 million over five years, an indication of the economic value of the centers to industry.

Introduction

The Nanoscale Science and Engineering Centers (NSECs) are charged with developing new areas of research and helping to establish a nanotechnology workforce. According to NSF, the centers are expected to address challenges and opportunities that are too complex and multi-faceted for individual researchers or small teams to tackle in shorter periods of time. Furthermore, the centers typically involve partnerships with multiple universities, industry, national laboratories, foreign institutions, and other sectors. The centers are required to support K-12, undergraduate, graduate and postdoctoral training and to advance the public understanding of nanoscale science and engineering. The first cohort of six NSECs was established in 2001. There were two new NSECs awarded in 2003 and six in 2004.

Exhibit V-1: Years of Operation of NSECs

Number of NSEC Awards Included in this Study	
Year	Number of Awards
2001	6
2002	0
2003	2
2004	6
Total	14

Source: NSEC Annual Reports, reporting periods 2001-2005

The scale of centers allows them to carry out these multiple functions, including fulfilling extensive reporting requirements that document all these activities. NSECs are required to report their activities in two separate formats: (1) as part of an annual report; and (2) in the NSEC Web data collection system located at http://chaffee.qrc.com/nsf/eng/nsecWeb/start.cfm. SRI collected annual reports from the 14 NSECs directly and gained access to the NSEC Web data collection system. In addition, SRI requested that NSEC PIs provide additional information about center activities in three areas: regional economic impact;[10] environmental health and safety; and societal and ethical implications. These activities are often described in the annual reports, but they needed to be confirmed as the annual reports are not always consistent even though the requirement is spelled out in the *Guidelines for NSEC Continuation Requests*. NSECs provide data that are relatively rich, detailed, and reliable, more so than the other programs studied in this project, and thus serve as a model.

Based on the data collected, SRI has put together a number of tabulations that follow, and prepared cumulative totals for all centers into five spreadsheets that appear in an electronic database available from SRI and NSF. In addition, to study trends over time, SRI organized data by year of operation for years one through five. The Year One Table in the database shows data from first year annual reports for all centers. For example, centers that began in 2001 will have 2001 reporting year data, while centers started in 2004 will have 2004 reporting year data in the Year One Table. Sums of all center outputs, their averages, and averages per year have been included in these tables. In addition, Table 1-8 in the database shows the sum and average of NSEC and ERC outputs for the reporting period 2005-2006 for comparison. SRI analyzed the data in these tables; the results are presented in the next section. Qualitative analyses and syntheses of annual reports have been conducted, supplemented by interviews with NSEC directors and staff as the need arose.

Support for NSEC by NSF and Others

In the 2005-2006 reporting year, NSF's NSEC budget shows that, together, NSECs spent $22.8 million for research, $4.0 million for education, $2.8 million for administration, $1.7 million for equipment, and $0.7 million for knowledge transfer, totaling $32 million. The cost share portion of the 2005 budget shows a total of $6.5 million for all NSECs. NSECs received a

[10] SRI received no reports of significant, realized regional economic impact from NSEC PIs.

total of $17.5 million from other sources, mainly from industry. Of the $22.8 million NSECs spent for research in 2005, $1.5 million was spent to support seed projects, or 6.5 percent of all NSF NSEC funding for research.

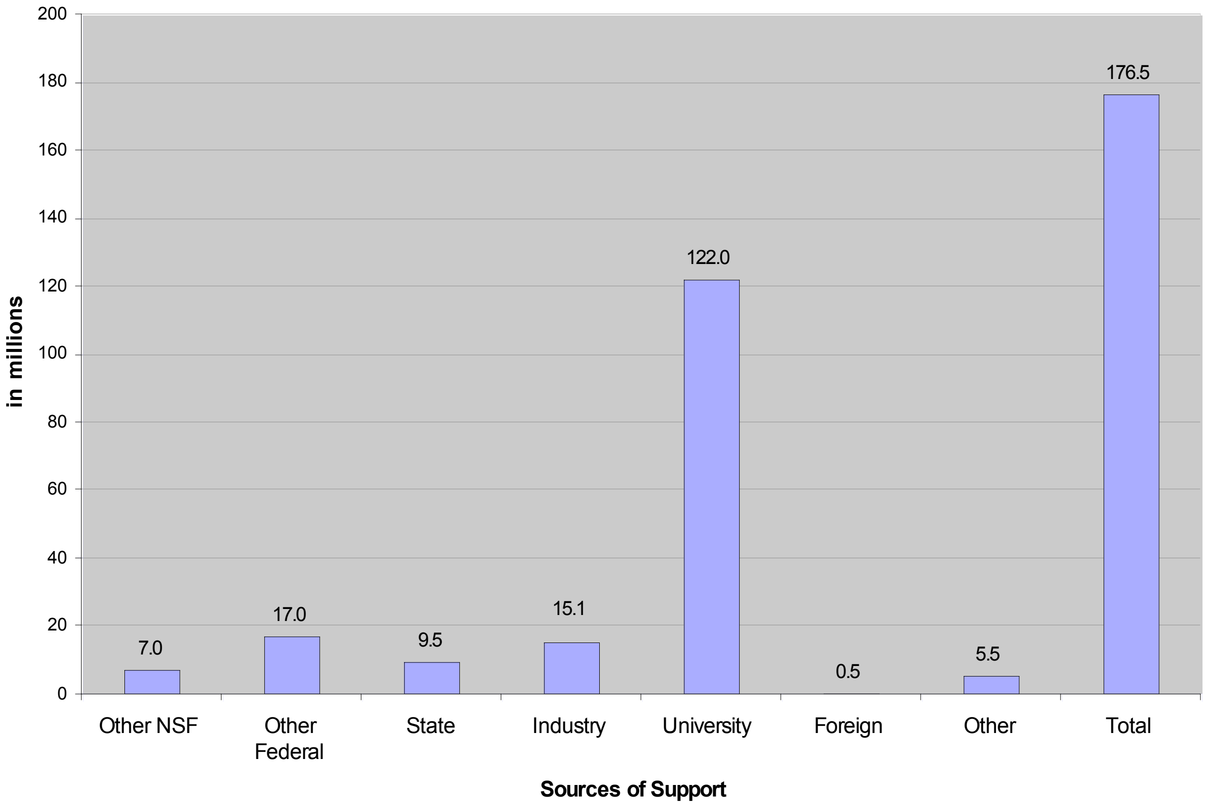
The cumulative total for 14 NSECs during all years of operation shows that NSECs received $92 million from the NSF NSEC program.[11] NSECs received and allocated $12.2 million from cost sharing to their budgets. They allocated a total of $62 million for research, education, administration, equipment, and knowledge transfer activities over time. NSECs received a total of $176.5 million from "other sources," of which $114.5 million was allocated for a new building at Harvard. Because the Harvard NSEC received these funds from the university, they were not included in the NSEC budget figures.

Financial support trends over time show no clear patterns. Annual NSF NSEC budgets vary year by year for all categories. For example, NSF NSEC funding for research peaked for centers in their third year at an average of $2.1 million per center, remaining at the $1.5-1.7 million level for the remaining years. Other support from various non-NSEC program funding sources shows a highly skewed distribution among centers, with older centers showing higher cumulative total leverage. However, even among the centers in the same cohort, there were great variations. Though some centers received no support at all from some of these other funding sources, others received a disproportionately high level of funding from some of them. Furthermore, it is not the same group of centers that successfully attracts major funding from all other sources; rather, some institutions attract high levels of funding from some sources, while not attracting support from other sources. The patterns are highly varied, except in the case of Harvard, which reported high levels of other support in most categories.

There was considerable variation among NSECs in the amount of "other support" by category during all years of operation. For example, among the 14 NSECs, six attracted funding from other federal agencies. Among those, Northwestern attracted the most, a cumulative total of $13 million from other federal agencies; Rice attracted $2.5 million. Support from state governments also varied greatly, with nine NSECs receiving no state support and four NSECs (Columbia, Cornell, Northwestern and Northeastern University) receiving over $1 million in state support, with Northwestern obtaining the highest amount at $3 million. Industry support also shows a highly skewed pattern, though the RPI NSEC is the only center that received no industry support[12]. Harvard and Rice each attracted about $5 million from industry. Harvard received a large amount of industry funding from the Semiconductor Industry Association (SIA) as a part of SIA's Nanoelectronics Research Initiative.

[11] Budget data were missing in the following annual reports: Rice 2001, 2002, 2003; Cornell, 2002; Northwestern, 2003; therefore all the cumulative numbers are likely an underestimate.
[12] RPI explained that they considered industry and state funding as cost sharing and included these funds in table 2 and not in table 5.

Exhibit V-2:
Cumulative Total of Other (Non-NSEC Program) Support



Source: NSEC Annual Reports, reporting period 2001-2005

Research Outputs

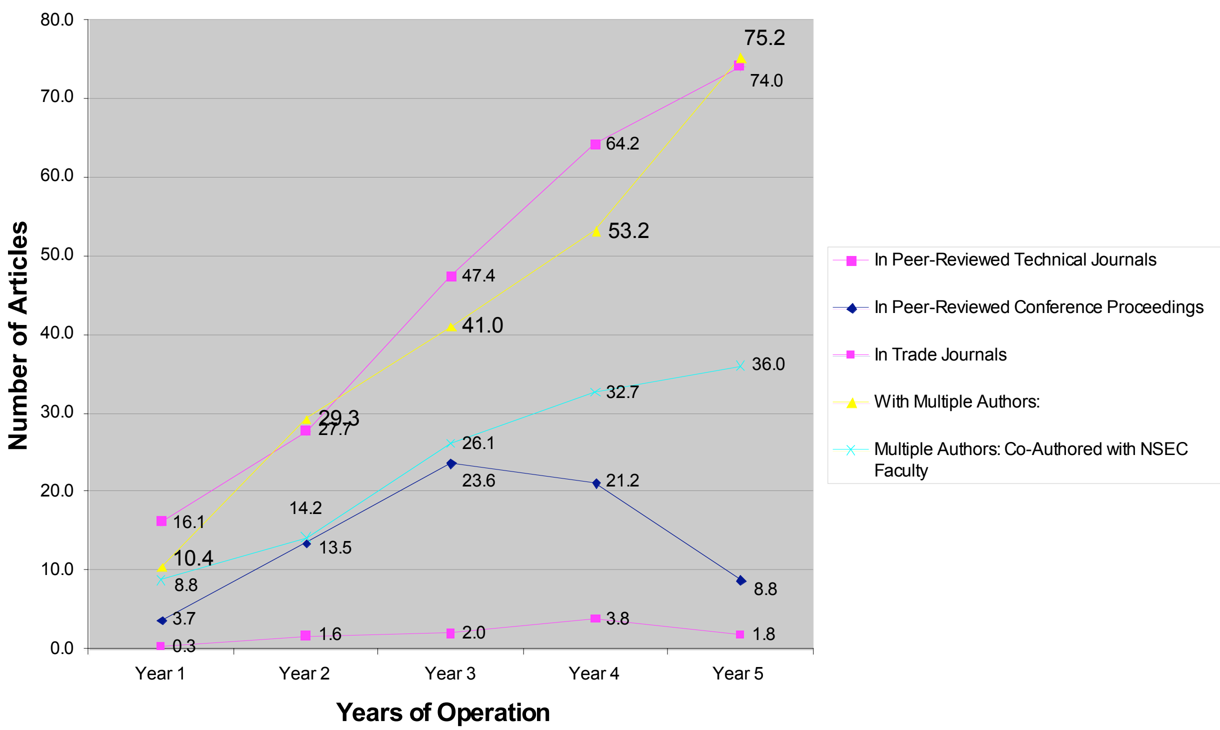
The number of publications per year from NSECs varies greatly by center. The number of publications reported in the database, Table 1-6: Quantifiable Outputs – Total for all Years, does not distinguish published papers resulting from full NSEC support from those resulting from partial NSEC support, while the annual reports make this distinction. It may be necessary to distinguish papers resulting from partial support and full support to obtain a more accurate picture of NSEC publication outputs. Though the NSEC Report Guideline spells out the requirement for counting NSEC publications, the fact that many different program directors in different NSF directorates are responsible for reviewing NSEC final reports may explain the great variation in publication numbers, as each program director may apply slightly different criteria for publication counts.

Even among the centers that started in the same year, publication records vary widely. Stanford University reported the fewest publications--only two. When asked about this, the Stanford NSEC director explained that there are several factors that contributed to the small number of publications: CPN is smaller than other NSECs; CPN faculties are in the early stages of their careers; the center is narrowly focused on tool development; and strict criteria are applied to publication counting.

The total number of publications in peer-reviewed technical journals reported by all centers for 2001-2005 is 1,822; 610 articles appeared in peer-reviewed conference proceedings and 77 articles in trade journals. Among these, 1,654 articles were published by multiple authors and 943 articles were co-authored with other NSEC faculty. Harvard has the highest number of publications, 440, which may have to do with their success in attracting other support. The average annual number of publications in peer reviewed technical journals per center is 38.[13] The number of publications generated by a typical NSEC increases over time, as one may expect. Exhibit V-3 shows that the number of publications in peer-reviewed technical journals and in conference proceedings also increases as centers mature.

Exhibit V-3:

Trends over Time: Average Number of Publications



Sources: Appendix C Table 1-1 to 1-5, NSEC Annual Reports, reporting period 2001-2005

Collaboration

Many NSECs partner with a number of universities in the U.S. and abroad, as well as with other types of research, education, and industrial organizations. NSECs were asked for the first time to report the number of partnering institutions in their 2006 annual reports (for the 2005-2006 reporting period). Except for the three NSECs in the 2004 cohort, most NSECs reported more than ten partnering institutions that participated significantly in the planning and execution of activities of the center. Northwestern and Harvard topped the list at 89 and 86

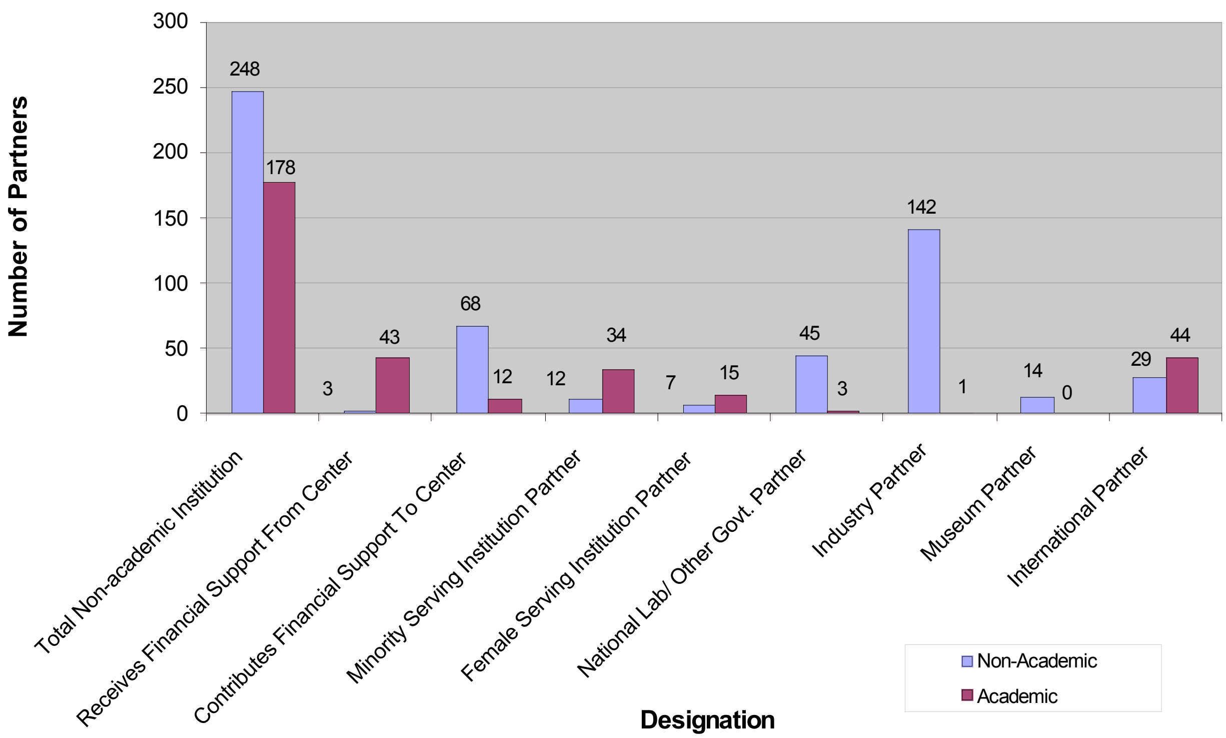
[13] The calculation is as follows: 1822 articles divided by the total number of years of operation of the 14 NSECs, which is 48.

partners, respectively. Overall, the 14 NSECs in this study reported 426 partnering institutions.[14] Among those, 46 partnering institutions received financial support from the NSECs, while 80 partners contributed financial support to centers. Over 90 percent (43) of the institutions who received financial supports from NSECs were academic institutions, while 85 percent (68) of the institutions who contributed financially to NSECs were in non-academic sectors. There were more non-academic institutions than academic institutions that collaborated with NSECs; industry tops the list at 143 partners.

NSECs collaborated with 46 minority-serving institutions and 22 female-serving institutions. They have collaborated with the following types of non-academic institutions: 48 national lab or other government partners, 143 industry partners, and 14 museum partners. NSECs collaborated with 73 foreign institutions from both academic and non-academic sectors in foreign countries.

Exhibit V-4:

Partnering Institutions for NSEC



Source: NSEC Annual Reports, reporting period 2001-2005

[14] The categories for partnering institutions are not mutually exclusive and can cause confusion. 2005 was the first year that NSECs were asked to provide this information, and there appear to have been some errors. For example, some NSECs listed national labs or industry partners as academic institutions, while others reported minority or female serving institutions as non-academic partners. The tables NSECs provided list the name of each institution and check all the categories that may apply to these institutions, so for example, the RPI NSEC reported "Smith College" as their partnering institution that receives financial support from the center, as a minority serving institution, and as a female serving institution. They also listed "ABB" as an organization that contributes financial support to the center, as an industrial partner, and as an international partner.

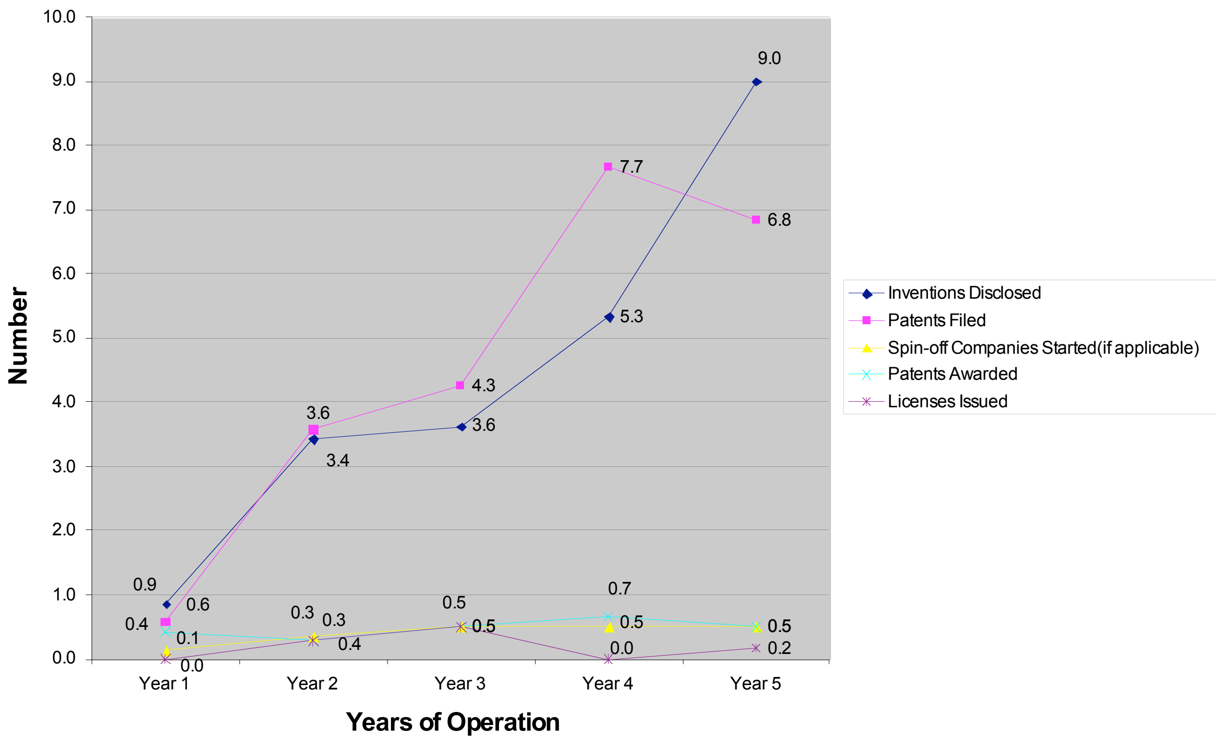
The average number of universities with which core researchers (faculty level) were affiliated in each center was 3.4. The NSEC at Ohio State has participants from nine universities, while the NSEC at Rice has only intra-institutional participants.

Economic Impact

Indicators of the economic output of NSECs take several forms. SRI examined trends in selected indicators over time to see if discernable patterns emerge as centers mature, e.g., inventions disclosed, patents filed, patents awarded, patents licensed, and spin-off companies. Among these five indicators, patents awarded and licensed did not show a clear pattern, but the other three show increases over time as centers mature.

Exhibit V-5:

Trends over Time: Technology Transfer Indicators



Source: NSEC Annual Reports, reporting period 2001-2005

To show trends over time for technology transfer activities, data for year one to year five in Exhibit V-5 draw on data from Table 1-1 to Table 1-5 in the database. These are the average number of NSEC activities when centers were at the same "age" or years of operation. For example, year one data show the average number of inventions disclosed, patents filed, spin-off companies, patents awarded, and licenses issued per center in their first year of operation (2001 for the 2001 cohort, 2003 for the 2003 cohort, and 2004 for the 2004 cohort), while year five shows the average numbers of these activities for the 2001 cohort in its fifth year of operation.

Technology transfer activities by NSECs vary by center, though all centers show some level of patent activity at various stages of the pipeline. The total number of economic outputs by all centers through 2005 is as follows: 175 inventions disclosed, 179 patents filed, 21 patents awarded, nine licenses issued, and 17 spin-off companies created. Harvard filed for the most patents (46), though Northwestern reported the highest number of invention disclosures (59). Cornell and University of Pennsylvania reported the highest number of patents awarded, four each. Six centers reported no patents awarded. Five NSECs reported the creation of spin-off companies based on center research. Among those, four centers are from the 2001 cohort. A total of 17 spin-off companies were started from NSEC research. Northwestern and Harvard again stand out, having created six and four spin-off companies, respectively. Three NSECs issued licenses; the greatest number was issued by UCLA (7).

Another indicator of potential economic impact is industry support for NSECs. The assumption is that firms will pay for NSEC membership if they perceive the benefit equals or exceeds the cost of the membership fee, sponsored research projects, and cash and in-kind support (if provided). In that sense, the total amount of industry support is an indication of the economic value of NSECs for member firms. There are other benefits to industry such as students hired, workshops offered to industry, and exchanges of researchers, each of which would have additional but unknown economic impact, so this estimate of economic value is very conservative. Industry support for NSECs for all years totaled $15.1 million, averaging $314,818 per year per center. Harvard and Rice each attracted about $5 million from industry. Six NSECs in the 2004 cohort, operating for just two years, have attracted far less industry support, none of them attracting over $1 million, with three of them attracting less than $100,000. The number of students hired by industry is 42 for all NSECs, and the number of students hired by NSEC member firms is five.

NSECs hosted industry researchers for research collaboration as follows: 13 for all centers in year one, ten for year two, six for year three, seven for year four, and 14 for year five. It is not shown if any of them stayed more than a year, so it is impossible to calculate the total number of industry researcher-years involved. One unique feature of the Stanford NSEC is that it is collaborating with IBM, not through membership but via a formal joint effort between Stanford University and IBM, the Stanford/IBM Center for Probing the Nanoscale.

NSECs offered a total of 123 workshops and short courses to industry, but the number varied greatly by center. Those NSECs that attracted a high level of industry support and filed a large number of patent applications, such as Harvard (29) and Northwestern (32), offered more workshops and short courses to industry, while half of the NSECs offered three or less.

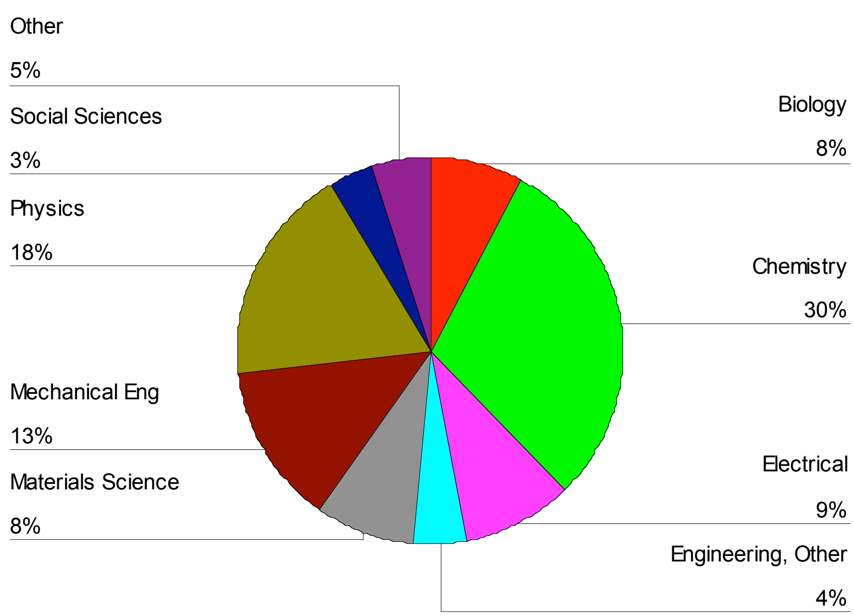
Interdisciplinarity

A quick glance at the departmental affiliations of faculty-level participants in each center shows an unusually high number of different departments involved with each NSEC. To begin with, 149 out of 413 faculty-level participants appear to be affiliated with multiple departments. About 36 percent of the NSEC individual participants are affiliated with multiple departments, suggesting that NSECs tend to attract researchers with appointments in more than one department. For tabulation purposes, after noting their multiple departmental affiliations, these

149 faculty researchers were coded with the name of their first departmental affiliation, assuming that the first department listed is their primary affiliation[15].

One can argue that some departments, even traditional ones such as geology, are inherently interdisciplinary. However, the existing university departmental structure is an indication of disciplinary boundaries. SRI categorized the names of each department by the field of study code used by the NSF Survey of Doctoral Recipients. Then, we counted the number of department names of faculty participants in each center and found that the average number of departmental affiliations is 9.1. The total number of fields of study counted from all 413 NSEC faculty members was 44. Participants in six NSECs came from over ten different departments. NSECs stand out for having participants from a wide range of departments, including rather unusual disciplines such as history, anthropology, economics, management, and philosophy. Chemistry and chemical engineering grouped together had the highest number of participants in NSECs, 123. Next were mechanical engineering, physics, materials science, bioengineering, and electrical engineering.

Exhibit V-6: Departmental Affiliation: NSEC Faculties



Source: NSEC Annual Reports, reporting period 2001-2005

[15] It is a judgment call to decide from a name whether it refers to multiple departments or is the name of a single department. To be consistent, SRI strictly followed NSF's field of study table. Thus, if the table lists a compound name as separate fields of study, SRI counted it as a multiple departments. By this standard, for example, Electrical and Computer Engineering was counted as multiple departments, while biochemistry was counted as a single department, even though Electrical and Computer Engineering is a very widely used name for a single department.

Education and Training

The annual average number of doctoral degrees awarded by each NSEC is three. Through 2005, a total of 148 doctoral, 57 masters, and 53 bachelors degrees were awarded to students in all 14 NSECs. 154 new courses were created based on NSEC research. Ten new textbooks, three degree programs, five minors, and five certificate programs were established based on NSEC research. NSECs offered 739 workshops and short courses to others (non-industry), 3,655 seminars and colloquia, and 19 World Wide Web courses.

For the 2005-2006 reporting period, Berkeley reported 813 education program participants at the undergraduate level, which is clearly an outlier given that five NSECs reported no undergraduate education program participants, and most centers have less than a hundred undergraduate education program participants. The fact that Berkeley reported establishing a full degree program may explain this unusually high number of education program participants. On the other hand, at the K-12 level, all NSECs except Berkeley have K-12 education participants, ranging from three students at UCLA to 3,500 at Wisconsin. As a part of outreach efforts to the general public and K-12 schools, many NSECs partnered with local science museums and organized programs designed to enhance public understanding of nanotechnology. NSECs have collaborated with a total of 14 museum partners. Most centers participated in the REU program in one form or another, but two centers (RPI and Stanford) did not participate. SRI inquired of the RPI NSEC why they have not participated in the REU program. RPI has its own program called the Primarily Undergraduate Institution (PUI) program; participating institutions are top schools including three women's colleges and two HBCUs. Therefore, while providing top students and engaging faculties from research-performing universities, the PUI program has the added benefit of providing a diverse group of students a chance to get involved in NSEC research.

The RET program is less utilized by NSECs; only eight out of the 14 NSECs reported participation by RET teachers. Only Columbia, Stanford, and Northwestern reported any industry researchers directly participating in research or education projects, a total of 19. However, many NSECs have non-RET programs designed for K-12 teacher participation, and the number of teachers participating in non-RET programs is relatively large in many centers. Furthermore, many NSECs have implemented training programs for K-12 school teachers, numbers not captured in Table 4-6: NSEC Personnel–Yearly Totals, but are included in Table 3-6: Educational Program Participants-Totals found in the database. For example, in the 2005-2006 reporting year, 1,299 teachers participated in various K-12 education activities hosted by NSECs.

Environmental, Health and Safety Implications

NSECs are engaged in research activities concerning environmental, health and safety (EHS) issues to varying degrees. On the one hand, some NSECs take EHS as their core mission, such as the Center for Biological and Environmental Nanotechnology at Rice University. The core goal of the Rice NSEC includes engineered nanoparticles that detect and treat diseases, and high performance nanoparticle-based water treatment systems. Also, the Berkeley NSEC's core mission is to develop personal and community-based environmental monitoring (PACMON) and reduce the size, weight, noise, energy consumption, cost, sensitivity, and selectivity of monitors used by residents and environmental watch groups. The NSEC at RPI reported that several projects in Thrust two (Nanostructured Biomolecule Composite Architectures) have been highly successful in contributing to the fundamental understanding of nanoscale material interactions at the molecular and cellular level through *in vitro* and *in vivo* experiments and models. On the other hand, several centers such as those at Cornell and the University of Pennsylvania do not consider EHS to be a part of their research activities. Many others did not report much activity on EHS issues other than lab safety, except for Rice, Berkeley and RPI.

NSECs appear to take the issue of lab safety seriously. For example, the Columbia NSEC requires each researcher to receive basic training from the Columbia University Office of Environmental Health and Radiation Safety or the equivalent as a condition for participating in the center research. Other NSECs implemented a similar lab safety training programs.

Societal and Ethical Implications

NSECs have designed and implemented creative programs and activities to address societal and ethical implications. Most NSECs are proactive in addressing the societal impacts of nanotechnology, responding to both public fear and concern for the safety of nanotechnology on the one hand and public expectations for potential economic and social benefits of nanotechnology on the other. The program solicitation for the nanoscale science and engineering activity at NSF, of which NSEC is a part, requires successful awardees to design in activities addressing the societal ramifications of advances in nanoscale science and technology.

Many NSECs regard the mandate to address societal impact as a part of their core mission and support research on this topic as one of their major research thrusts. As a result, researchers from social sciences, humanities, and management actively participate in NSEC research. Furthermore, NSECs participated in public forums of various kinds: they built partnerships in private and public sectors; supported researchers from social sciences and humanities; offered workshops and other educational opportunities for K-12 teachers, students, and the general public; cooperated in museum exhibits; and reached out to media professionals.

For example, the NSEC at Columbia University is involved in the Converging Technologies Bar Association (CTBA), an organization that seeks to provide a forum to discuss the legal, ethical, and societal issues generated by the convergence of nanotechnology, biotechnology, information technology, and other related fields. The ethical conduct of research was also incorporated as a part of the NSEC curriculum at Columbia University.

The sixth thrust of the Berkeley NSEC is to maintain close connection between technology development and societal needs and ramifications. Social science researchers at the Cornell NSEC focused on the public understanding of nanotechnology and the dynamics of industry-university collaboration in real time as participant-observers.

The Northeastern University NSEC includes the study of environmental, economic, regulatory and ethical impacts of nano-manufacturing as a part of their main research thrusts. The Northwestern NSEC put together an interdisciplinary committee with representatives from philosophy, theology, ethics, public policy and law as a forum open to scientists and the lay public. The Ohio State University NSEC implemented a plan to develop comprehensive methods of systematic analysis of ethical, societal, and environmental aspects of new medical nanotechnology.

The Rice University NSEC formed an International Council on Nanotechnology (ICON) to address risk management for nanotechnology, which has been successful in drawing in financial support from industry for its mission, and put together a database of peer-reviewed literature in nano-environmental, health, and safety issues. The Rice NSEC also sponsored the Science Café, a public forum held at a local coffeehouse featuring local scientists in a discussion moderated by a local newspaper reporter. Rice has also taken the role of advising the Children's Museum of Houston.

The RPI NSEC, in collaboration with the Department of Science and Technology Studies on the same campus, has looked at how various institutions such as university, government, media, industry and the general public play roles in developing technology, and how the public perceives nanotechnology. RPI developed "Molecularium"—an animated movie designed to teach children about molecules and atoms in fun ways--and now even plans to bring it to IMAX theaters.

The Stanford NSEC is taking part in another NSF-funded initiative, the Nanoscale Informal Science Education (NISE) Network, the goal of which is to expand informal education efforts to inform the general public about nanotechnology. Among other things, the Stanford NSEC collaborates with local museums, artists, and teachers to develop educational materials that visualize the nanoscale phenomenon.

The UCLA NSEC collaborated with RAND in conducting a study to assess the potential societal impact of nanotechnology. The NSEC at the University of Pennsylvania organized a workshop for journalists and Nanoday, an event designed to raise public awareness of nanotechnology for the general public, and conducted a study on risk perception with respect to nanotechnology.

At the University of Wisconsin, the NSEC's fourth research thrust is an interdisciplinary research initiative investigating the economic, environmental, privacy, regulatory, and security implications of nanoscale science and engineering. This NSEC awarded a summer teacher fellowship and offered online courses to teachers.

Nanotechnology in Society Network/Center for Nanotechnology in Society (CNS)

A collaborative NSEC comprised of separate NSF awards to four "nodes," Harvard, the University of South Carolina, Arizona State University, and the University of California at Santa Barbara, was initiated in the Fall of 2005. The nodes began operations in late 2005 and early 2006, so it is premature to expect significant output or impacts at this time. However, the four nodes of the network are actively engaged in planning and/or initial implementation stages of research and education, training and development, research, and outreach focused on the societal implications of nanotechnology development and application. The four center partners submitted annual reports in July 2006, covering from six to nine months of activities. A sampling of these activities, drawn from these reports, provides an overview of the scope of this collaborative NSEC's goals and outputs to date.

Research at UCSB is organized into three working groups. The first group is interacting with UCSB nano-scientists and engineers as well as extramural scientists, mapping networks and the historical connections among spintronics researchers. The second is initiating innovation studies aimed at the relationship between risk perception and public engagement. The third is targeting the globalization of nanotechnology. At Harvard, as part of the effort to construct NanoIndicators, researchers are comparing nano with other areas of high tech activity. Others there are analyzing trend data on media articles about environmental and health risks in the U.S. and the U.K. as an indicator of the information the lay citizenry is getting and how that information is related to public concerns about nanotechnology. Under the aegis of the ASU center, researchers are conducting workforce supply and demand analysis in three regional labor markets and developing empirically-based insights about the dynamics of the NSE enterprise—its direction, velocity, synergies, and linkages—using publications, patent, and other data.

Training and development activities at UCSB emphasize recruitment of undergraduates, graduate fellows, researcher participation, and public outreach as mechanisms for increasing the diversity of the student population engaged in studying nano phenomena. Their outreach activities include a Website and clearinghouse intended to "share tools and resources generated for our own research, education, and public outreach programs to a wider audience." In addition, they have implemented a program of CNS nanoscience Graduate Research Fellowships to involve at least four nanoscience and engineering graduate students in the center's research. At South Carolina, researchers have already made more than 50 presentations and published seven journal articles. The center at USC has also sponsored nine undergraduate scholars in the 2005-2006 academic year. (This center benefits from having a previous NIRT award overlapping the CNS award in time and personnel.) One of the USC research projects builds specifically on the work done in the NIRT "Stabilization of Phenomena" research project.

Notably, the Harvard center's outreach activities to industry will flow from NanoConnection.net, their Internet portal to databanks and indicators, to Lehigh University's 50-member Nanotech Network as well as to other industry partners of universities in the project. Harvard (in collaboration with UCLA) has initiated pilot development of a NanoEthics Bank and a NanoEnvironment Bank, and begun gathering data for a NanoIndicator Series. Their research and education activities seek to gather and disseminate "high quality vetted information, based on empirical data, to serve as a community resource related to nanotechnology and society."

Comparing NSECs and ERCs

The following table, comparing outputs from NSECs and ERCs for the reporting period 2005-2006, was drawn from the 2006 annual reports for NSECs and the 2006 Web-based data collection system for ERCs (downloaded on September 6, 2006). NSECs collectively have had 48 years of operation while ERCs collectively have had 113 years of operation, over twice the life span of NSECs. Therefore, in considering time-sensitive variables such as number of patents granted or number of degrees awarded that tend to increase as centers mature over time, the difference in years of operation must be taken into account. Overall, NSECs appear to be as productive as ERCs in most categories, despite the fact they are "younger" than ERCs collectively, and sometimes exceed ERCs, e.g., in the number of publications in peer-reviewed technical journals--NSECs produced 50 articles per center while ERCs published 30 articles per center during the 2005-2006 reporting year. In technology transfer, ERCs generated more patents granted and patents licensed per center, but the average number of inventions disclosed and patents filed are the same. NSECs are slightly more successful in creating spin-off companies than ERCs. ERCs have granted far more degrees at all levels. NSECs show a relatively higher percentage of students graduating with doctoral degrees, which may explain the higher portion of NSEC students hired in academia, while very few NSEC students were hired by industry. NSECs and ERCs are similar in their per center impact on curriculum development and information dissemination/educational outreach. On average, NSECs produced more seminars and colloquia than ERCs. Overall, these patterns suggest that NSECs are more academically focused, while ERCs have stronger relations with industry.

Exhibit V-7: Comparison Table: NSECs vs. ERCs for the 2005-2006 Reporting Period

Outputs	NSEC 14 centers		ERC 16 centers	
Publications Resulting From NSEC Support	**Total**	**Average**	**Total**	**Average**
In Peer-Reviewed Technical Journals	697	49.8	477	29.8
In Peer-Reviewed Conference Proceedings	170	12.1	642	40.1
In Trade Journals	22	1.6	27	1.7
With Multiple Authors:	712	50.9	1178	73.6
Multiple Authors: Co-Authored with NSEC Faculty	386	27.6		
NSEC Technology Transfer				
Inventions Disclosed	93	6.6	108	6.8
Patents Filed	79	5.6	90	5.6
Patents Awarded	8	0.6	40	2.5
Licenses Issued	6	0.4	50	3.1
Spin-off Companies Started (if applicable)	5	0.4	4	0.3
Degrees to NSEC Students				
Bachelor's Degrees Granted	18	1.3	144	9.0
Master's Degrees Granted	19	1.4	142	8.9
Doctoral Degrees Granted	63	4.5	160	10.0
NSEC Graduates Hired by				
Industry:	24	1.6	148	
Member Firms	2	0.1	45	2.8
Other U.S. Firms	22	1.6	103	6.4
Government	3	0.2	12	0.8
Academic Institutions	38	2.7	96	6.0
Other	4	0.3	11	0.7
Unknown	7	0.5	94	5.9
NSEC Influence on Curriculum				
New Courses Based on NSEC Research	49	3.5	32	2.0
Courses Modified to Include NSEC Research	85	6.1	108	6.8
New Textbooks Based on NSEC Research	5	0.4	4	0.3
Free-Standing Course Modules or Instructional CDs	28	2.0	54	3.4
New Full Degree Programs	0	0.0	2	0.1
New Degree Minors or Minor Emphases	3	0.2	2	0.1
New Certificate	3	0.2	1	0.1
Information Dissemination/Educational Outreach				
Workshops, Short Courses to Industry	48	3.4	56	3.5
Workshops, Short Courses to Others	132	9.4	189	11.8
Seminars, Colloquia, etc.	1,430	102.1	815	50.9
World Wide Web courses	9	0.6	19	1.2

Sources: NSEC Annual Reports, reporting period 2005-2006; Appendix C Table 1-8. Quantifiable Outputs - Reporting Period 2005-2006; Engineering Research Center Monitoring System, End of Year Analysis Workbook http://chaffee.qrc.com/nsf/eng/ercweb/monitor/erc_mon0.cfm

VI. National Nanotechnology Infrastructure Network (NNIN)

Key Findings - NNIN

- In operation only since March 2004, 1,734 papers related to NNIN were published or presented at conferences in the 17 month period ending July 2005.
- 89 percent of these papers had more than one author, suggesting collaboration.
- Partners in NNIN activities were drawn from 11 different academic fields, led by materials science and MEMS.
- The cost of lab use per hour averages $30 for the period March 2005-February 2006. This relatively low cost suggests that NNIN has been efficient in providing NSE infrastructure.
- NNIN trained over 4,140 users and students during March 2005-February 2006.
- More than 3,200 graduate students per year have conducted research at NNIN facilities.
- 32 spin-off companies emerged from activities using NNIN facilities during March-December 2005.
- For March 2004-February 2006, industry represented 14-15 percent of users, with small companies representing 10-11 percent, a larger percentage than big companies.
- NNIN sites collected $16 million in user fees during March 2005-February 2006; half the users were self-funded.
- NNIN workshops in 2005-2006 hosted more than 700 people.

Introduction

The National Nanotechnology Infrastructure Network (NNIN) is a network of shared, open facilities distributed throughout the country with state-of-the-art equipment and expertise to support research in nanoscale science and engineering. Established in 2004 as a follow-on to the National Nanofabrication Users Network (NNUN), its central mission is to provide hands-on NSE research access for researchers from industry, government, and academia. NNIN provides the opportunity for these researchers to build and explore materials, structures, devices and systems using a combination of bottom-up and self-assembly techniques and top-down fabrication techniques. The network also has in place national and local efforts in support of education, public outreach, safety, and a mission to examine the societal and ethical implications of nanotechnology.

The Network began operating in March 2004, drawing together the research facilities and capabilities of 13 sites at research universities. The sites are:

- The Cornell Nanoscale Facility at Cornell University
- The Stanford Nanofabrication Facility at Stanford University
- The Solid State Electronics Laboratory at the University of Michigan
- The Microelectronics Research Center at the Georgia Institute of Technology

- The Center for Nanotechnology at the University of Washington
- The Penn State Nanofabrication Facility at the Pennsylvania State University
- Nanotech at the University of California at Santa Barbara
- The Minnesota Nanotechnology Cluster (MINTEC) at the University of Minnesota
- Nanoscience @ UNM (at the University of New Mexico)
- The Microelectronics Research Center at University of Texas at Austin
- The Center for Imaging and Mesoscale Structures at Harvard University
- The Howard Nanoscale Science and Engineering Facility at Howard University
- The Triangle National Lithography Center at North Carolina State University (unfunded affiliate).

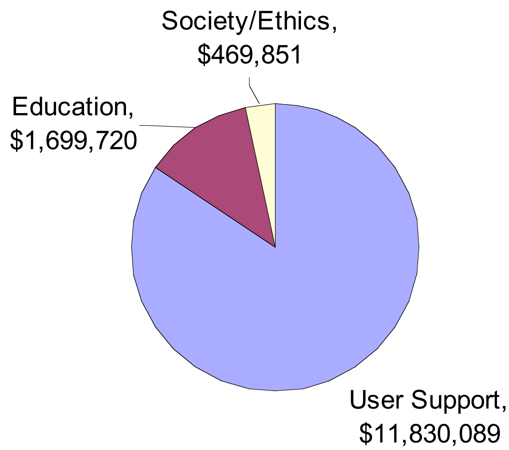
Each site brings both geographic reach and unique capabilities to the network:[16]

- Cornell and Stanford -- complex integration projects
- Georgia Tech and University of Washington -- biology and life-sciences
- Penn State, Harvard and Texas -- chemistry at the nanoscale
- New Mexico and Minnesota -- geosciences
- Michigan -- integrated systems
- Texas -- tool development and manufacturing research support
- Minnesota and New Mexico -- remote use and characterization
- North Carolina State -- 193 nm deep ultra-violet lithography.

The NNIN brings together about 850 major tools and pieces of scientific equipment representing about $250 million in investment, about 150 full-time-equivalent (FTE) people, and about 80,000 sq. ft. in clean room space as resources for the research support objectives. NNIN facilities include essentially all of the country's university-based 100 keV e-beam lithography machines, the premier biology-, chemistry- and manufacturing-tools-oriented nanotechnology efforts, and the country's leading systems-oriented process integration facilities. The NNIN also maintains a Web portal to provide virtual services, technical information, details on NNIN services, and outreach activities for education and discussion of social and ethical issues. Exhibit VII-1 shows funding by activity. The great bulk of funding (85 percent) goes for user support, 12 percent goes for education, and 3 percent for societal and ethical implications.

[16] Five of these facilities were previously members of the National Nanotechnology Users Network (NNUN): Cornell, Stanford, UCSB, Penn State, and Howard University.

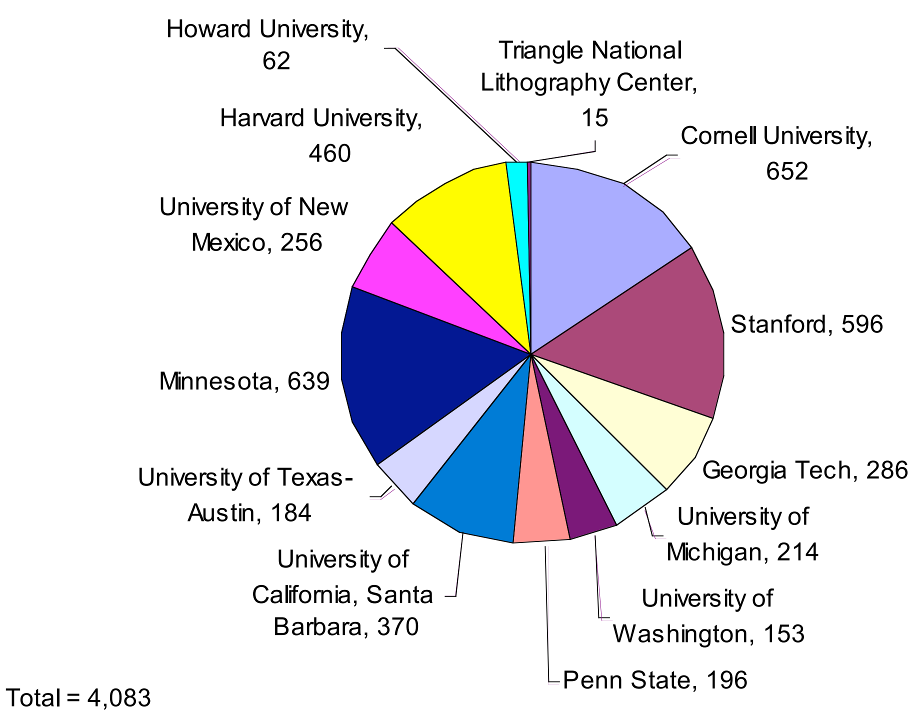
Exhibit VI-1: NNIN Funding by Activity, March 2005-February 2006



Source: NNIN Annual Report, 2005-2006

Exhibit VI-2:

NNIN Number of Users, by Site, March 2005-February 2006



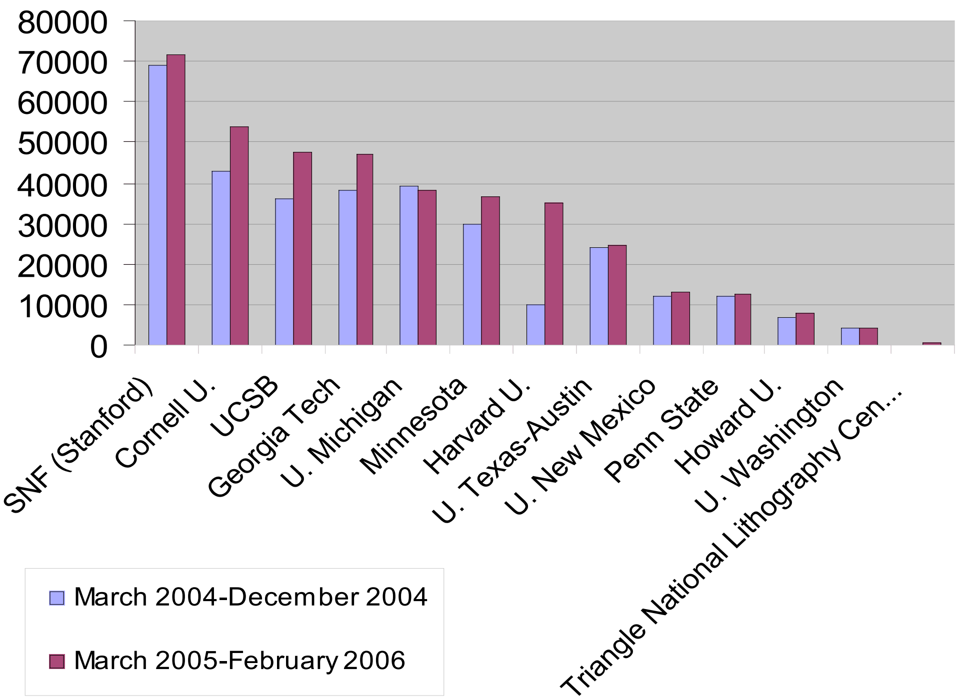
Source: Data courtesy of Lynn Rathbun, NNIN, and analyzed by SRI International

Exhibit VI-2 shows the number of users at NNIN sites, March 2005-February 2006. The centers with the largest number of users are Cornell, Minnesota, and Stanford University.

The number of cumulative hours for all users for all sites combined was close to 400,000 hours for the 2005-2006 year. Exhibit VI-3 shows the cumulative lab use hours by site for two periods, March 2004-December 2004 (10 months) and March 2005-February 2006 (12 months). (Exhibit VI-3 overstates the growth because the first year has only 10 months.)

Exhibit VI-3:

Cumulative Lab Use Hours for all Users, by Site, 2004-2006

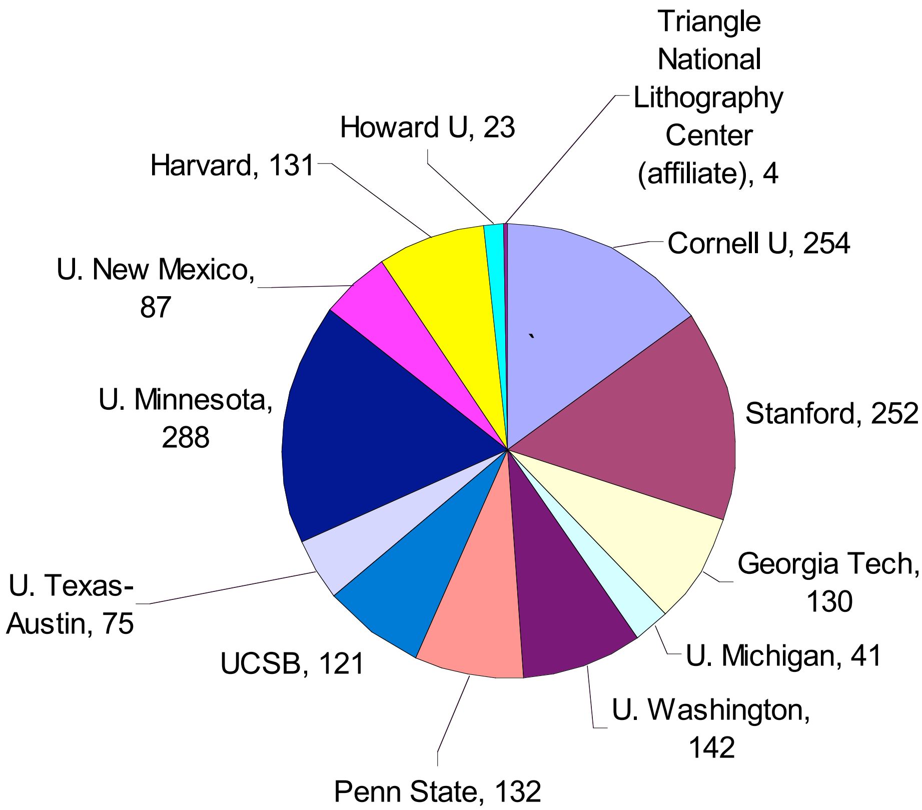


Source: Data courtesy of Lynn Rathbun, NNIN, analyzed by SRI International

Overall growth of lab user hours from the first to second year was modest (as was the growth in total number of users). However, the number of new users grew by more than 40 percent at the same time, perhaps offering promise of more substantial growth in subsequent years. (See Exhibit VI-4.)

Exhibit VI-4:

NNIN Number of New Users, by Site, March 2005-February 2006



Source: Data courtesy of Lynn Rathbun, NNIN, analyzed by SRI International

A breakout of new users by site is only available for 2005-2006. The site with the largest number of new users is Minnesota, followed by Cornell and Stanford University.

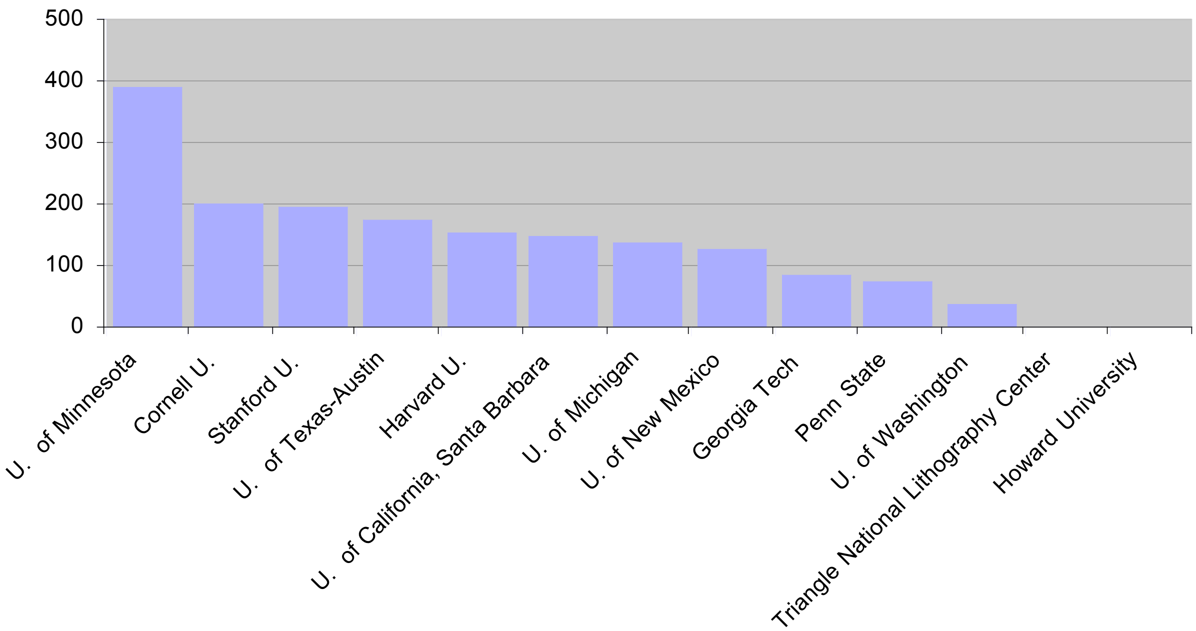
It is important to keep in mind that the NNIN sites are different in size, in funding commitments, and in their research focus. Different research foci differ in how intense they are in consuming staff or equipment time, so any comparisons should be considered in that context. The level of effort required to support a user performing advanced transmission electron microscopy is quite different from a user using simple fabrication, for example.

Research Outputs

One example of knowledge output is the number of peer-reviewed publications and conference presentations that result from research conducted at the NNIN facilities and assisted by NNIN staff. Users reported to NNIN staff that 1,734 papers were submitted and conference presentations made that were in some part related to research done at NNIN from March 2004–July 2005. The University of Minnesota far outpaced other network member institutions in reporting publications and presentations. (See Exhibit VI-5.)

Exhibit VI-5:

**Number of Publications and Presentations, by Site,
March 2004-July 2005**



N = 1,734

Source: Data courtesy of Lynn Rathbun, NNIN, analyzed by SRI International

Collaboration

The primary type of collaboration of interest with respect to NNIN is collaboration among researchers who use the facilities. The vast majority (1,536 or about 89%) of the publications and presentations resulting from research conducted at NNIN[17] facilities had more than one author, suggesting a great deal of collaborative activity as part of the research. Information is not available on the institutional or disciplinary affiliations of the authors, but the distribution of NNIN users by institutional type and field provides insight into the potential for collaboration. Usage of NNIN facilities by user institutional type is measured in terms of hours of usage, number of unique users, and number of new users, as shown in Exhibit VI-6.

[17] The publication list did not provide authors for 62 publications.

Exhibit VI-6: Usage of NNIN Broken out by User Institution Type As Measured by Hours of Usage, Number of Users, and Number of New Users, Two Periods, March 2004 – February 2006

	Lab Use Hours	Unique Users		New Users Trained	
Institution Type	**Mar. 2005-Feb. 2006**	**Mar. 2004-Dec. 2004**	**Mar. 2005-Feb. 2006**	**Mar. 2004 – Dec. 2004**	**Mar. 2005-Feb. 2006**
Local Site Academic	289,754	2,372	2838	682	1088
Small company	40,335	421	437	138	169
Other university	39,058	497	574	198	298
Large company	17,297	153	165	48	67
State & Federal Government	2,959	38	49	25	28
Foreign	920	0	11	7	4
2-year college	895	38	10	18	5
4-year college	396	38	42	28	14
Pre-college	373	268	12	140	7

Source: Numbers for March 2005-February 2006 were obtained from Lynn Rathbun, NNIN. The numbers for March 2004-December 2004 came from the 2004-2005 Annual Report, Fig. 7; estimated from bar chart.

All three indicators show that the local site academic users dominate users from all other types of institutions—with about 74 percent of usage in hours and 69 percent of number of users. We consider that this might change over time as the NNIN sites become better known in the wider community, although the number of new users for March 2005- February 2006 shows a large majority of new users (65 percent) still based at the local site university. Based on these data, most collaboration appears to be occurring within the host institutions.

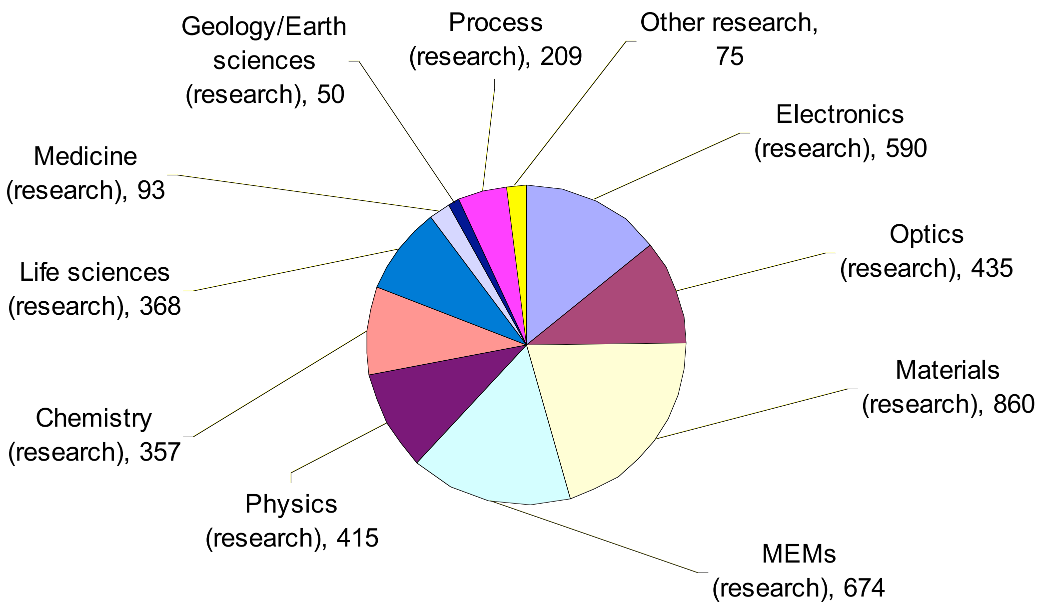
Other (non-local) universities account for another 10 percent of usage by hour or 14 percent by number of users. Colleges that are primarily teaching institutions (i.e., two- and four-year colleges) account for 1 percent or less of usage. These institutions probably participate in only a small proportion of the collaborations.

NNIN sites shows that the fields of science or engineering being drawn to use the facilities are fairly evenly spread among 11 fields; see Exhibit VI-7, which shows the number of users, by field.

Materials research is the largest category of users and also the largest category of new users (as seen in Exhibit VI-8). MEMS/Mechanical Engineering Research and Electronics Research are the largest categories by lab use hours. The highest potential for collaboration exists within and among the fields that are most highly represented among users.

Exhibit VI-7:

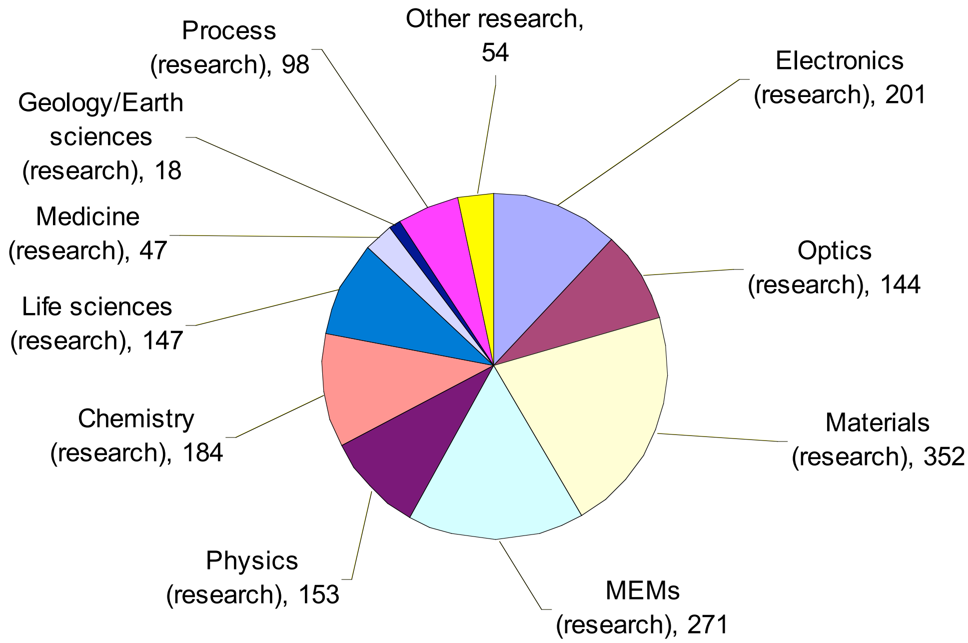
**Number of Users, by Field,
March 2005-February 2006**



N = 4,083
Source: Data courtesy of Lynn Rathbun, NNIN, analyzed by SRI International

Exhibit VI-8:

New Users Trained, by Field, March 2005-February 2006



N = 1,680
Source: Data courtesy of Lynn Rathbun of NNIN, analyzed by SRI International

Another type of collaboration possibly of interest is collaboration between NNIN support staff and researcher/users. NNIN's interaction with its users is a form of collaboration. There is certainly knowledge transfer between staff and users. Every new user is trained in safety and rules, and in operation and use of a variety of tools. Moreover, process knowledge is shared from staff to users and from one user to another, both informally one-on-one as well as through a variety of short courses that are offered.[18]

NNIN staff report that they contribute to essentially all NNIN user projects in some way, either through training, education, or direct project assistance. This is particularly true when working with users from outside the NNIN site. Currently 31 percent of NNIN users are from outside the local academic host institutions. (For example, Cornell University is the local academic host institution for the Cornell Nanoscale Facility (CNF).) This number is higher at the former NNUN sites, but it is growing at the new NNIN sites as their programs build.

Network facilities and staff at the sites and on-line serve an average of 1,800 users each month from more than 11 different fields of science or engineering. The majority of NNIN users are from universities (83 percent), with the remaining users coming from four- and two-year

[18] Personal communication.

colleges, pre-college educational institutions, industry, and foreign users. More than 250 small companies used the facilities during the period March 2005-December 2005.

Because NNIN is built upon a user facility model, however, collaboration between staff and users in the sense of "inventing things together" is avoided so that users do not have to sign intellectual property (IP) agreements that would permit the site institutions to lay claim to IP that might be generated through facilities/network use. In addition, most users want technical help not intellectual help[19].

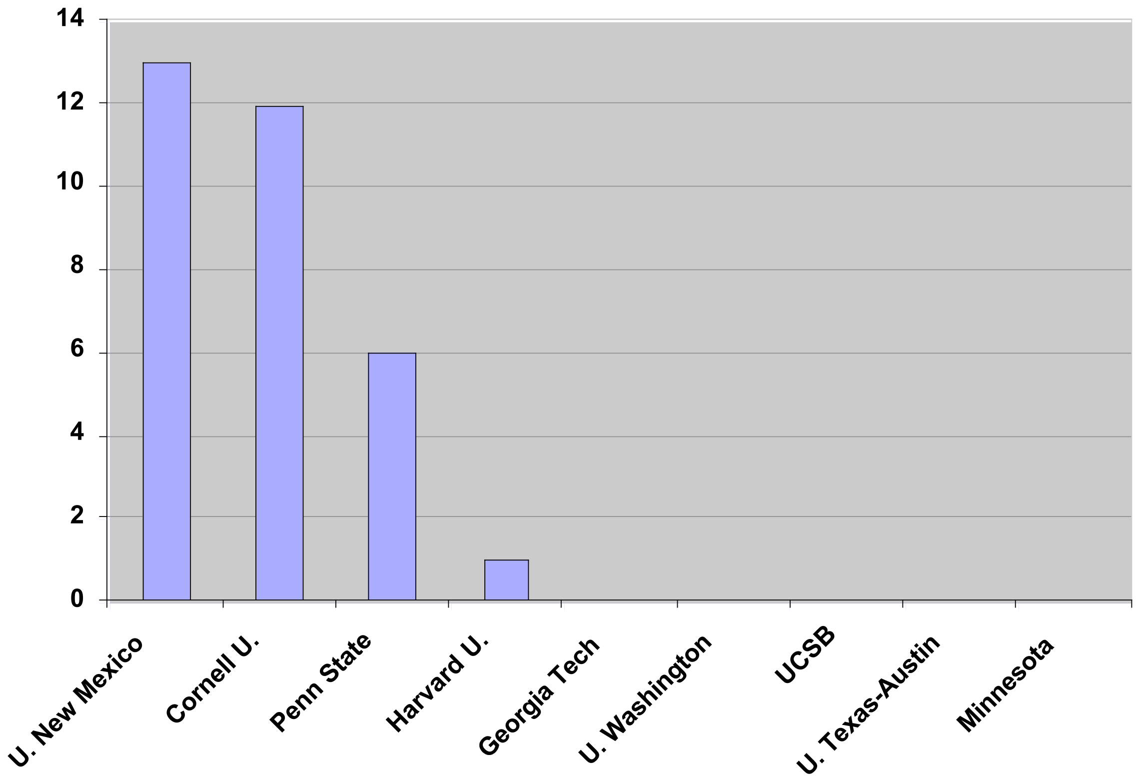
Economic Impact

The intermediate economic indicators we found show a small but significant output from the NNIN sites. Traditional indicators of intermediate economic output such as invention disclosures, patent applications, patents awarded, and software licenses are not collected by the NNIN sites and, in any event, it is too early in the Network's development to expect these kinds of outputs. Other indicators we found show the potential for economic impact, however. Four of the sites reported that they have "seeded" new businesses, totaling 32 small businesses that have started in part due to the use of NNIN facilities. Exhibit VI-9 shows the distribution of reporting of the small businesses "seeded" by reporting sites.

[19] Personal communication.

Exhibit VI-9:

Number of Small Businesses Seeded by NNIN Facility Technology, by Site, March 2005-December 2005



Note: Data were not reported by Howard, Stanford, or Michigan.
Source: Data courtesy of Lynn Rathbun, NNIN, analyzed by SRI International

As shown in Exhibit VI-6, small companies represent 10-11 percent of NNIN usage and are one of the larger user groups. Large companies represent a smaller proportion of usage, about 4 percent. The usage by large and small companies indicates a minor but significant flow of knowledge from the NNIN sites to the industrial sector, a possible precursor of technological innovations and economic development.

User fees indicate the minimum economic value of NNIN facilities and services as perceived by users. NNIN users paid about $16 million in user fees during March 2005-February 2006. Of this, industry paid $5.24 million; about two-thirds of this was paid by small companies and one-third by large companies. This indicates a significant economic value to the users. User fees at NNIN are charged on a per-user or per hour basis with the exact structure varying by site. They also change from time to time as individual sites need to adjust fees. External academic users are charged the same rate as local academic users. Industrial users pay the full cost of usage, while academic users benefit from lower costs that NSF support makes possible. Because of these differences it is not possible to use user fees to draw conclusions about differences in the economic value of NNIN services to different sectors, fields, or sites, or trends in economic value over time.

We also examined the extent to which users are self-funded (versus government-funded) as another indicator of the economic value of network access. These data are provided for some users. We were told by NNIN staff that about half of the users report themselves as "self-funded." Assuming that state and federal users, large and small business users, and foreign users were self-funded, we calculated that about $5.25 million in user fees or about one-third of the total were self-funded. This is an over-statement of the economic value of NNIN services to these users because it is known that some of the small business users are funded by outside parties such as government agencies and private foundations.

The cost per lab use hour averages about $30 for both years examined. This cost was calculated by dividing the total NNIN funding for user support per year by the cumulative lab use hours for all users for that year. This is an indicator of the efficiency of the NNIN in providing NSE infrastructure. According to knowledgeable sources, this cost is low compared to similar lab fees charged by other user facilities.

Interdisciplinarity

No data directly indicative of interdisciplinarity were available. However, the field distribution of users shows a breadth of backgrounds, as might be expected at a nano-site where interdisciplinary research tends to be the norm. We can make some assumptions about the fact that users from different fields will interact and possibly find opportunities for collaboration and knowledge transfer based on their co-location or connection through the NNIN sites. Exhibit VI-7 (above) shows the number of lab users by field, giving some indications of the disciplinary breadth of users who are working side-by-side.

Education and Training

NNIN makes a significant contribution to practical training in laboratory nanotechnology. Each of the 4,140 annual users is trained in the use of multiple instruments and techniques. This is generally done in a hands-on, face-to-face fashion by NNIN staff members. A total of 1,690 new users were trained in the 2005-2006 year of operation. The NNIN program manager observed, however, that training of new users is only a fraction of the total NNIN training and technology transfer activity.[20] Video training is also made available via the NNIN Website and the individual site Websites. Since many users have laboratories elsewhere, there is a considerable leveraging effect of this training as they return to their home laboratories.

More than 3,200 graduate students conduct research at NNIN per year and more than 1,000 PhD awards made every year depend on NNIN for conducting an important part of the research involved.[21] A coordinated network-wide program for Research Experiences for Undergraduates (REU) has been in place since 1997, at first among the five NNUN sites and

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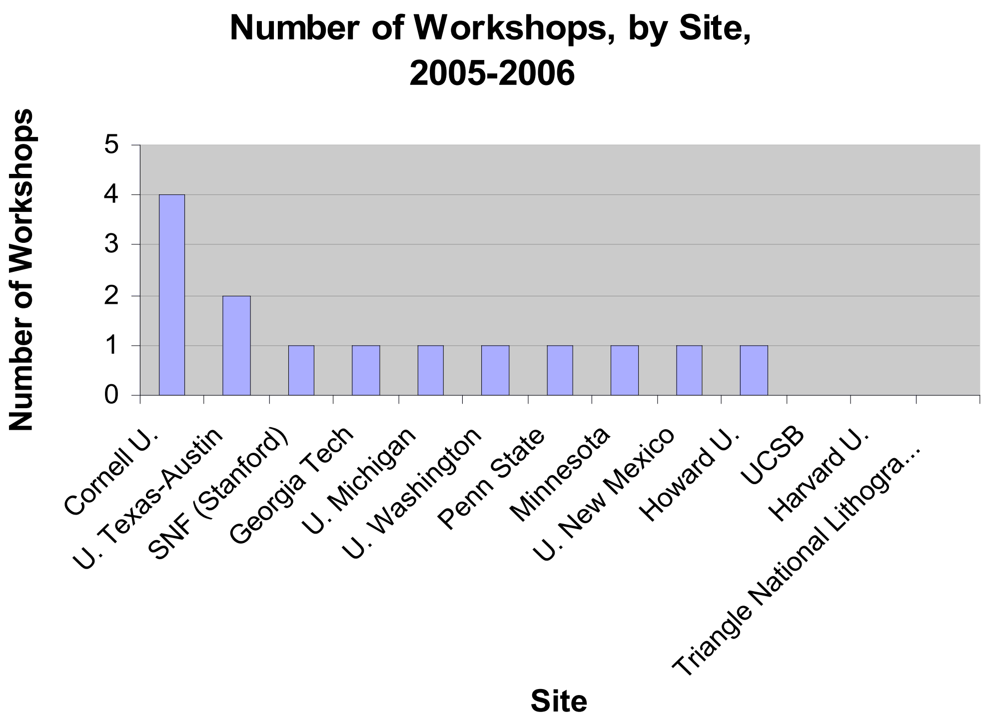
[20] Personal communication.

[21] From the February 2006 site review overview of the NNIN program, presentation by Dr. Sandip Tiwari.

then among the 13 NNIN sites. In 2005-2006, 81 REU participants were supported by the 13 NNIN sites, up from 72 in 2004, and much higher than the 41 REU participants supported at the five NNUN sites in 2003. Additional undergraduate students supported by other programs also used NNIN facilities in each of those years, but this number is not accurately tracked. It is estimated that more than 150 undergraduates conduct research at NNIN sites per year.[22]

Training and outreach to the larger scientific community is generally done via open workshops, either on specific technologies or on general nanotechnology capabilities, at each site. Fourteen such workshops were held in 2005-2006. NNIN provided the data in Exhibit VI-10, which shows the number of workshops and courses offered, by site. The NNIN PI reported that more than 700 people attended workshops in 2005-2006.

Exhibit VI-10:



Source: Data courtesy of Lynn Rathbun, NNIN, graphed by SRI International

Part of the K-12 outreach effort is the Research Experiences for Teachers (RET) program. Prior to 2006, several individual sites supported the RET program, with a total of ten participants in each of 2004 and 2005. For 2006, these separate programs have been combined into an NNIN network-wide RET program operating at five sites. This combination will bring more clarity and resources to the NNIN RET program and it is anticipated that the program will support at least 20 teachers annually.

[22] 2006 NNIN site visit, overview presentation *op cit*.

In addition to the network-wide education and training programs, individual sites also have activities focused on local needs, ranging from attracting underrepresented high school students through rewarding experiences to support for the local teaching community – high school, community college and other small colleges. Data on these activities have not been tracked systematically to date, but based on the statistics scattered through the descriptions in the Annual Reports it is clear that thousands of people have participated in them.

The REU program has quantifiable benchmarks regarding participants that include 50 percent women participants, 20 percent from underrepresented minorities, 50 percent from schools with no Ph.D. program in science and engineering, and 50 percent from outside the 100 largest research universities. Women and minorities have a higher participation rate in the program in comparison to the applicant pool. In its recent RET proposal, NNIN indicated a commitment to recruit teachers who are from underrepresented groups and teachers who teach in schools with high minority populations.

In addition to the Education Portal, the NNIN Website also includes lectures on the practice of nanotechnology, a variety of graduate-level discussions related to specific disciplines, lectures related to mentoring (the art of scientific presentation or of writing scientific papers), as well as instructional material related to social and ethical considerations.

Environmental, Health and Safety Implications

Quantitative indicators of the Environmental, Health, and Safety (EHS) activities of NNIN are not available. However, these activities are discussed in both the 2004-2005 and 2005-2006 NNIN Annual Reports. They are coordinated across the Network by a coordinator at Stanford.

NNIN recognizes two sets of EHS issues: 1) the occupational health and safety of laboratory workers and 2) the health and safety of the public exposed to nanotechnology products. Occupational health and safety of laboratory workers is an area where the NNIN sites have considerable experience and can make significant contributions. The training given new users of NNIN facilities is aimed at safety and thus a major part of NNIN's EHS activity. Each new user of NNIN (numbering 1,680 in 2005-2006) receives extensive health and safety training prior to use of the facilities. This initial training averages four hours per user, or more than 6,700 hours of training. Since each of these users also has laboratory facilities elsewhere, often at other institutions, there is a significant multiplier effect to this training. Much of the health and safety material is available on the individual sites' Websites.

According to the 2005-2006 Annual Report, safety training materials developed at NNIN sites are shared via the NNIN Website with other NNIN sites and with users around the world. The contents of the original Cornell Nanoscale Facility (CNF) Laboratory Usage and Safety Manual, for example, can be found in use in many laboratories around the world. The manual has been copyrighted to assure that the program receives recognition for its contribution in this area.

NNIN has organized workshops on EHS, focused on the NNIN sites and a broader audience. These workshops have addressed a number of the EHS issues identified by NIOSH as safety and health concerns associated with nanotechnology.[23] Examples include the following events:

- Stanford and Cornell organized a workshop, "Nanosafe," at Georgia Tech on the Health and Safety Aspects of Nanotechnology in December 2004 with over 40 attendees. Speakers included representatives from Stanford, NIOSH, and the University of Arizona, among others.
- In October 2005, Minnesota co-organized, with NIOSH and other agencies, the 2nd International Symposium on Nanotechnology and Occupational Health, a four-day conference held in Minneapolis.
- Minnesota organized the 7th International Aerosol Conference Date: September 10-15, 2006, including a Special Symposium on Nanotechnology and Occupational Health.

Societal and Ethical Implications

The goal of the Social and Ethical Issues (SEI) component of NNIN is to increase the national capacity for exploring the social and ethical issues associated with nanotechnology. To accomplish that goal, the SEI component is developing an infrastructure for conducting research and disseminating information about SEI. These activities are centered at Cornell, Stanford, Washington and Georgia Tech. The internal infrastructure to address this goal consists of SEI coordinators at each NNIN site, who help organize talks, panels, seminars, courses, or other activities involving SEI. They also facilitate the conduct of research on SEI at their sites. The output of these activities is then distributed via the SEI Website portal, workshops, presentations, and peer reviewed publications.

The first two years of SEI activity focused on building and strengthening the SEI infrastructure. The SEI component also contributed to the NNIN-wide REU program by stimulating discussion of social and ethical issues. The NNIN SEI portal (located at http://sei.nnin.org) is the central face for SEI efforts within NNIN. The site is intended as an archive of all materials related to social and ethical implications of nanotechnology and to act as a resource and a research tool for the SEI community. The SEI portal was put up in 2004 and completely updated in 2005.

[23] See http://www.cdc.gov/niosh/topics/nanotech/critical.html#exp

The SEI component includes funding for research on issues in ethics, innovation, workforce development, and history of nanotechnology. Examples follow:

- Cornell's Lead researcher: Bruce Lewenstein. Ongoing research on public communication of science and technology, including media coverage and public opinion.
- The University of Washington Lead researcher: Suzanne Brainard. Network-wide project for assessment of diversity and opportunity in the nanotechnology workforce.
- Georgia Tech Lead researcher: Marie Thursby. Ongoing research on innovation and productivity of large firms in nanotechnology, with particular attention to intellectual property and comparisons with biotechnology.
    - ❖ Four publications in 2005
- Stanford Lead researcher: Robert McGinn. Ongoing survey of the SEI awareness and attitudes of over 1000 nanotechnology professionals in the NNIN community. This is believed to be the first large scale survey of the nanotechnology community.

In addition to research and general support, many of the NNIN sites contribute or host substantial guest-lecturing, public lectures, collaborations, courses and course materials, and other activities related to SEI. For example, all REU students in 2005-2006 received an introduction to Social and Ethical Dimensions of Nanotechnology, which featured an introductory video, readings, and discussions.

Members of the NNIN SEI community contributed to a number of publications, projects, panel presentations, and conferences. Panels were held at the American Association for the Advancement of Science (AAAS) in 2005 and 2006, and a presentation on SEI in nanotechnology education at the American Society for Engineering Education in June 2006.

VII. Network for Computational Nanotechnology (NCN)

Key Findings-NCN

- During September 2003 through June 2006, NCN has deployed 40 simulation tools and more than 50 different educational resources on NanoHUB, whose users now number 12,000+ per year.
- Simulation users now number 2,300 per year.
- 359 publications have resulted from NCN-supported research since 2002.
- Since NCN's inception in 2002, nearly 16 percent of NCN publications have been coauthored across multiple engineering disciplines, and nearly 22 percent have been coauthored across engineering and non-engineering disciplines. The number of co-authored publications resulting from NCN-related activities has increased between 2002 and 2005.
- Industrial users have been increasing and accounted for 8 percent of users in 2005.
- Users from outside the U.S. now constitute 45 percent of all simulation tool users.
- The average number of co-authors of NCN publications in 2005 was 4.6, suggesting significant levels of collaboration.
- NCN principal investigators come from eight academic disciplines, led by electrical and computer engineering.
- From 2004 through 2006, 23 degrees were awarded to NCN students, of which 12 were Ph.D.s.
- NCN supported 26 REU students and 53 Summer Undergraduate Research Internship students in 2005.
- Since 2002, NCN PIs have developed 25 new courses.

Introduction

Founded in 2002, the Network for Computational Nanotechnology (NCN) aims to accelerate the transformation of nanoscience to nanotechnology by making modeling and simulation vital to all members of the research community. As articulated by the NCN program staff and principal investigators, the mission of the program is *to create, deploy, and operate a national resource for theory, modeling and simulation in nanoscience and nanotechnology, using cyberinfrastructure to build, serve, and benefit simultaneously from capabilities in research, education, design, and manufacturing.*[24]

The NCN's scientific focus includes three thematic areas:

- Nanoelectronics
- Nanoelectromechanical systems (NEMS)/ nanofluidics, and
- Devices for nanomedicine.

[24] Network for Computational Nanotechnology Fourth Annual Report, Vol. 1, p21, May 2006.

While research in the first two themes is intended to advance science and develop tools to understand nanoscale devices, the nanomedicine theme provides an intellectual test bed in which the new knowledge and software developed in the nanoelectronics and NEMS themes are used to explore new devices for medicine and biology.

Operationally, the NCN is organized into three planes of activities:

1) **Knowledge generation**. Multidisciplinary and multi-institutional teams of faculty and students at the participating universities conduct theoretical and experimental research in the three aforementioned scientific themes. The outputs of their research comprising scientific knowledge, software, and educational resources feed into the other planes of activities.
2) **Technology development and deployment**. The development and deployment of software and middleware technologies integrates knowledge created through research, hardens the software, optimizes algorithms, and produces multimedia educational content.
3) **Cyberinfrastructure and Web presence through NanoHUB**. This component of the NCN focuses on enabling access to content, simulation tools, and software to a broad community of nanoscience researchers.

Thus, the NCN acts as a resource for the nanoscience and technology community by creating new knowledge, delivering the knowledge in usable format such as tools, algorithms, and software, and enabling access to those through Web-based infrastructure to a global community of researchers.

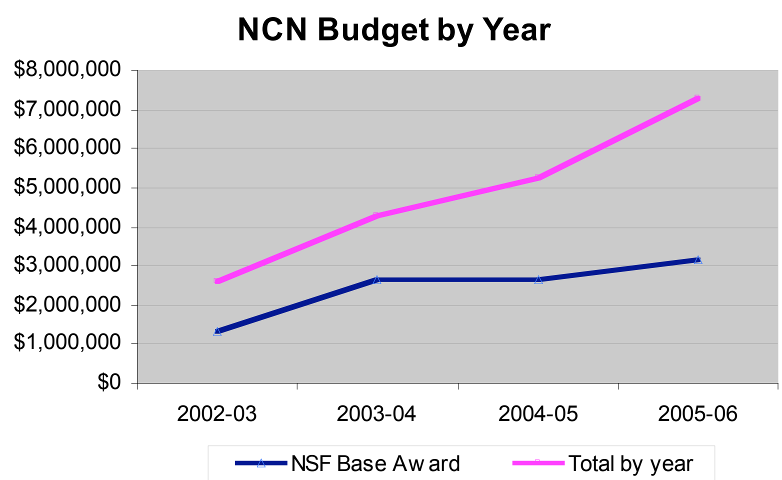
The NCN is set up as a collaboration of eight academic institutions, with Purdue University serving as the hub of the network and MIT, Northwestern University, University of Florida, University of Illinois at Urbana-Champaign, Stanford, Norfolk State University, and University of Texas at El Paso serving as the nodes. As the lead institution, Purdue hosts and maintains the NanoHUB, the core cyberinfrastructure part of the NCN, and provides overall program management and leadership in software development and educational technology assessment. While each participant university provides multidisciplinary research teams with a broad range of expertise relevant to the various components of NCN, each partner institution offers leadership in a specific area and a set of capabilities. For example, Northwestern focuses on computational chemistry, Illinois on nanomedicine and biology, Florida on middleware, and Stanford on the transition of research codes to CAD tools; UTEP and Norfolk State are outreach partners in developing nanoscience research programs.

For computing and cyberinfrastructure, the NCN has developed strong partnerships with the NSF-funded TeraGrid and with the Open Science Grid. The NCN is constantly upgrading its architecture and has developed and deployed middleware based on IN-VIGO, a distributed environment that provides users with their own secure virtual environments in which to run applications -- all coexisting on the same physical resource. The integration of this new middleware into a distributed grid-based job management system (Condor) has enabled NanoHUB users to seamlessly access computing resources available through TeraGrid, drastically reducing the amount of time it takes to run their jobs.

Collaborating with the Open Science Grid, the NCN has created a NanoHUB virtual organization (VO) which allows other institutions to contribute resources to the NanoHUB infrastructure as well as allows NCN resources to be used by other scientific collaborations.

The NCN has completed four years of operation, during which the level of resources available for development and operation of the network have tripled. As illustrated in the following chart, the NCN received a little over $2.5 million in funding in its inception year 2002-03. Of this total, $1.3 million, or nearly 50 percent, was in the form of direct support from the NSF. Purdue University provided the balance of funds as a cost share. In 2005-06, the NCN received $7.3 million in support from various sources including over $3.1 million from NSF's base award. The NSF also provided $1.42 million in other forms of support, including a $1 million funding through its NSF Middleware Initiative (NMI). Collectively, NSF support constituted over 62 percent of NCN's funding for the year.[25]

Exhibit VII-1:



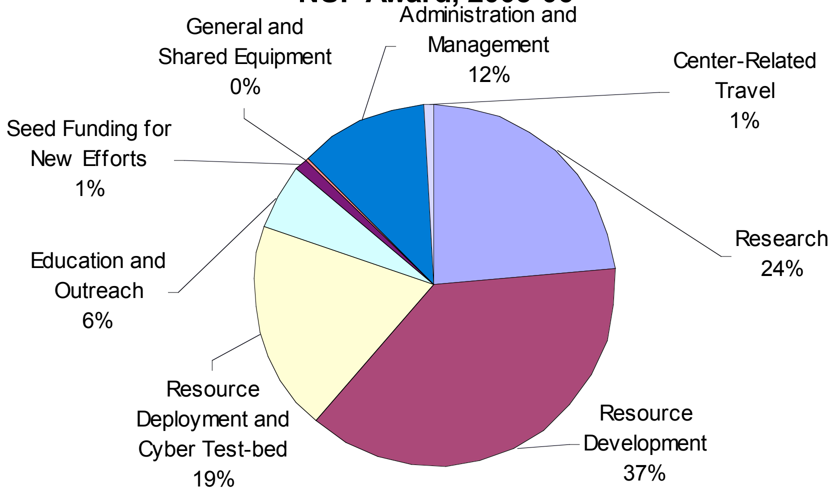
Source: NCN's 4th Annual Report & Revised Proposal to NSF

In 2005-06, a little less than a quarter of the funds provided by NSF through its base award for NCN were spent on research. Nearly 56 percent of NSF's direct support was spent on resource development and deployment of the NanoHUB. When funds received from all sources are taken into account, the share of resource development and deployment increases to 58 percent and the share of research increases to 28 percent of all funds allocated to NCN activities. The following charts present a detailed breakdown of funds allocated to various activities in 2005-06.

[25] SRI estimates based on data reported by the NCN in Table 3 (Sources of Support) in the 4th Annual Report and Renewal Proposal to NSF, May 2006.

Exhibit VII-2:

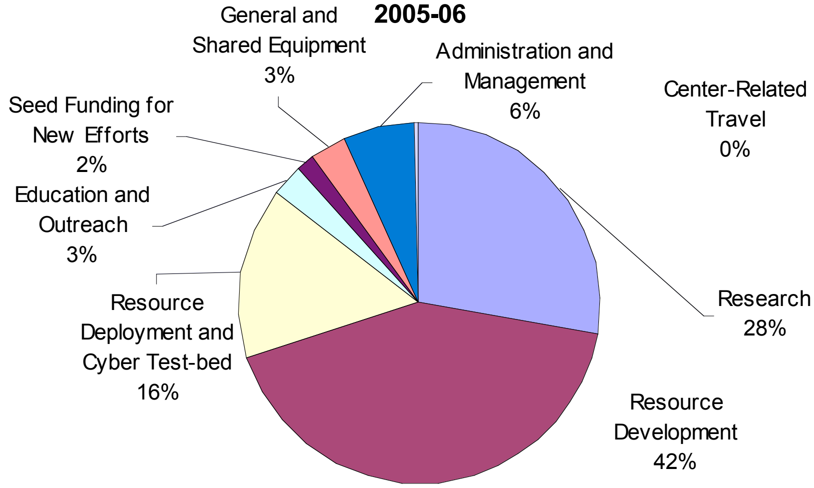
Allocation of Funds Received through Direct NSF Award, 2005-06



Source: SRI International and NCN's 4th Annual report to NSF

Exhibit VII-3:

Allocation of Total Funds Received by NCN, including Direct Support and Associated Project Support from All Sources, 2005-06



Source: SRI International and NCN's 4th Annual report to NSF

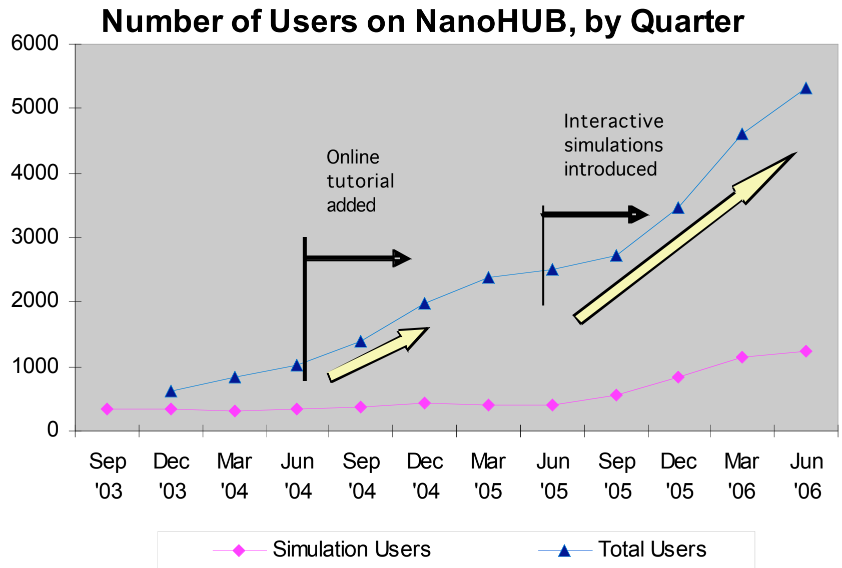
It must be noted that resources brought to NCN by node universities and funds allocated to them have increased in recent years as node universities have become increasingly more engaged in all aspects of NCN's activities, including research, resource development and deployment, and education and outreach. The role of the node universities is further expanding with the establishment of the "NCN@university" program, which intends to engage other on-campus centers and nanotechnology researchers, to train and assist local users with NCN technology such as Rappture, and promote the use of the NanoHUB for educational programs on and off campus. The NCN provides a modest level of support for research on numerical algorithms, visualization, and middleware, as well as seeding new science areas. Through these research efforts, it has developed and continually leverages key partnerships with other large-scale nanoscience and technology initiatives such as the NSF National Middleware Initiative, the NSF TeraGrid, and the Open Science Grid.

NCN's multidisciplinary teams of researchers have used these resources to advance theory, modeling, and simulations in nanotechnology and to make the products of their research and development available to the public. NCN's open source approach to software development and access has led to a rapid adoption of its products and infrastructure by a broader research community in recent years. During the past four years, the NCN has produced new knowledge in each of its science themes, designed and deployed a robust cyberinfrastructure, and deployed over 40 simulation tools and more than 50 different educational resources on the NanoHUB. Over 12,000 users[26] per year now use the NanoHUB, and the number doubles each year. The following chart plots, by quarter, the number of users running simulation jobs using tools available on the NanoHUB. It also plots the total number of users, including simulation users, users exploring educational content and downloading course content, animations, seminar proceedings, etc.

Historically, there were approximately 1,000 users of the cyberinfrastructure developed at Purdue, most of them being registered simulation users[27]. In late 2003, NCN began to add seminars, animations, and other teaching materials, as well as new simulation applications. The number of total users started increasing rapidly, although the number of simulation users remained at the historical levels until the middle of 2005, when the next round of upgrade was added. NCN launched new middleware enabling rapid development and deployment of interactive applications, and the number of simulation users has now reached more than 2,300 annually.[28]

[26] An active user is a unique IP address spending at least 15 minutes on the NanoHUB or a registered user who runs at least one simulation.
[27] NanoHUB's predecessor PUNCH served about 1,000 simulation users annually from 1994 to 2002.
[28] Matthew Potrawski, Administrative Director of NCN indicated that these two "take-off" points represent two major milestones in the history of the program.

Exhibit VII-4:



Source: SRI International and NanoHUB Website (www.nanohub.org)

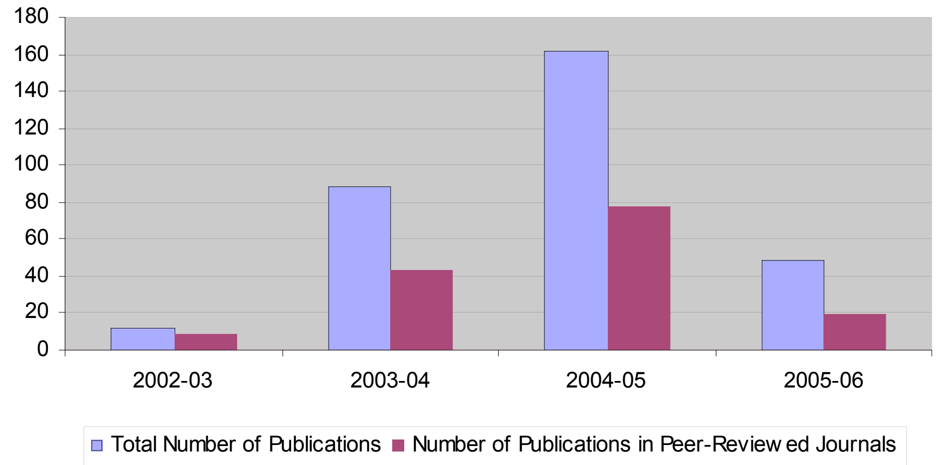
Research Outputs

While NanoHUB is the primary vehicle for knowledge dissemination for NCN, NCN researchers have also published widely in peer-reviewed journals and conference proceedings. 359 publications have been reported by NCN researchers since the inception of NCN in 2002. The total number of NCN publications increased from 12 in 2002-03 to 162 in 2004-05, but declined to 48 in 2005-06.[29] Exhibit VII-5 provides an annual breakdown of NCN publications.

[29] In a telephone interview with the SRI team, Matthew Potrawski, NCN's Administrative Director, reasoned that it is the NCN management's decision to apply stricter guidelines on what should be counted as an NCN publication than a shift in focus away from research to user orientation that caused the decline in the count of NCN publications in 2005-06.

Exhibit VII-5:

Trends in NCN Publications

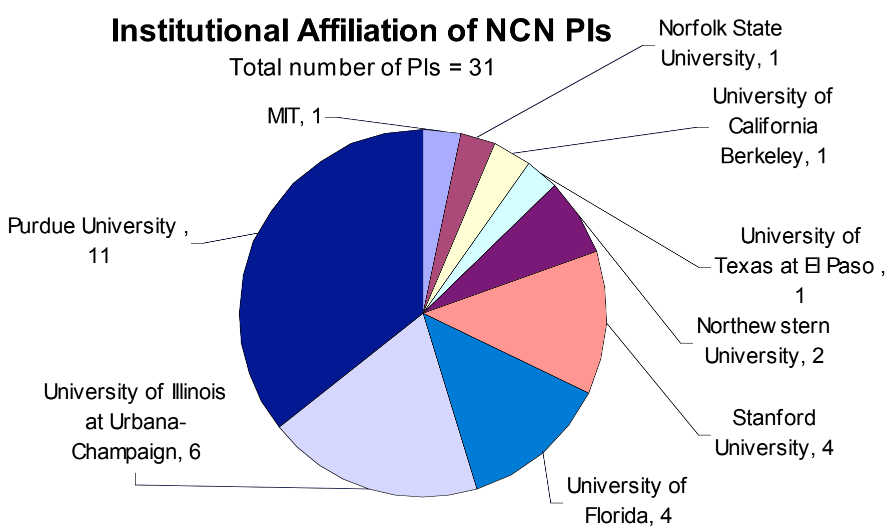


Source: NCN's 4th Annual Report & Revised Proposal to NSF

Collaboration

The NCN program is a collaborative effort by design. The 31 principal investigators of NCN represent nine premier academic institutions in the United States. In addition, NCN researchers collaborate with multiple U.S. and overseas academic institutions outside the network, industry, and government labs.

Exhibit VII-6:



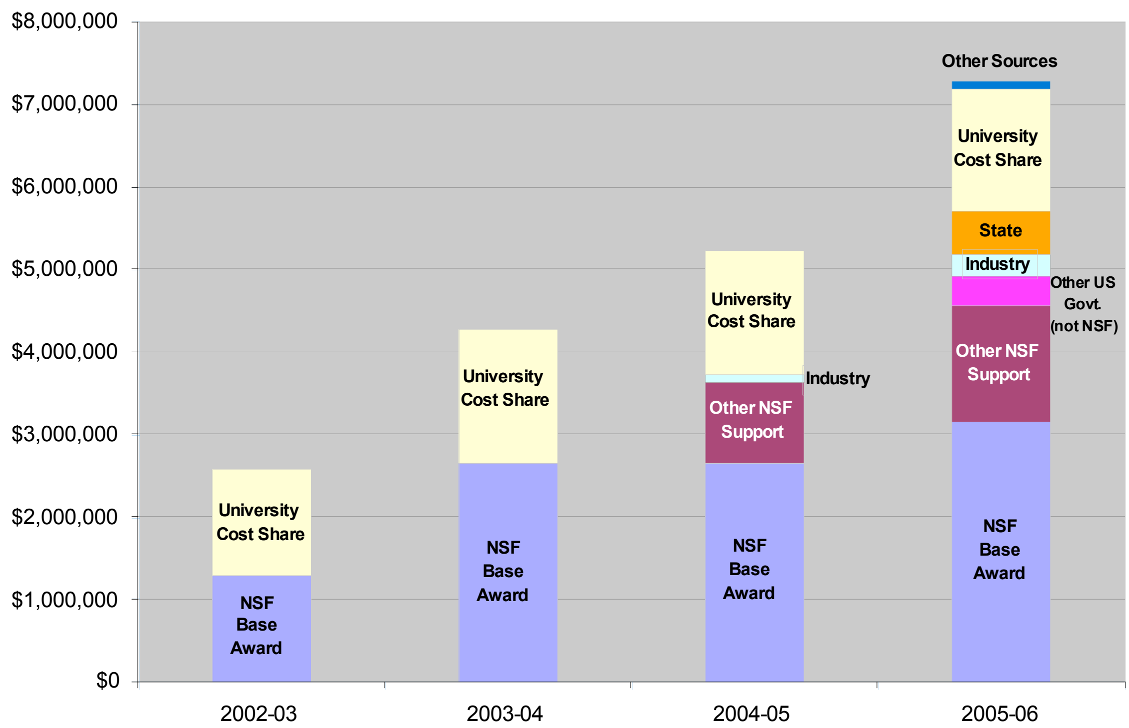
Source: SRI International, 2006

NCN has established research partnerships with the Quantum Science Research group of Hewlett-Packard, the Nanoscale Science and Technology Group of IBM, and the Silicon Nanotechnology Research Group of Intel Corporation. NCN researchers also conduct many joint projects with NASA Ames Center for Nanotechnology, NASA's Jet Propulsion Lab, and DOE's National Renewable Energy Lab.

NCN's mission to advance nanotechnology and its emphasis on computational infrastructure have attracted interest from multiple private and public sector (State and Federal) organizations. This interest in joint research and collaboration with NCN is reflected in the total resources made available to NCN by the partnering organizations. The following chart captures the direct and indirect support received by NCN from various sources. While the NSF base award and Purdue University's cost share provided all of NCN's resources in the first two years, the later years have seen an infusion of resources from industry, other federal agencies, and States.

Exhibit VII-7:

Funds Received by NCN, by Year and by Sources of Support

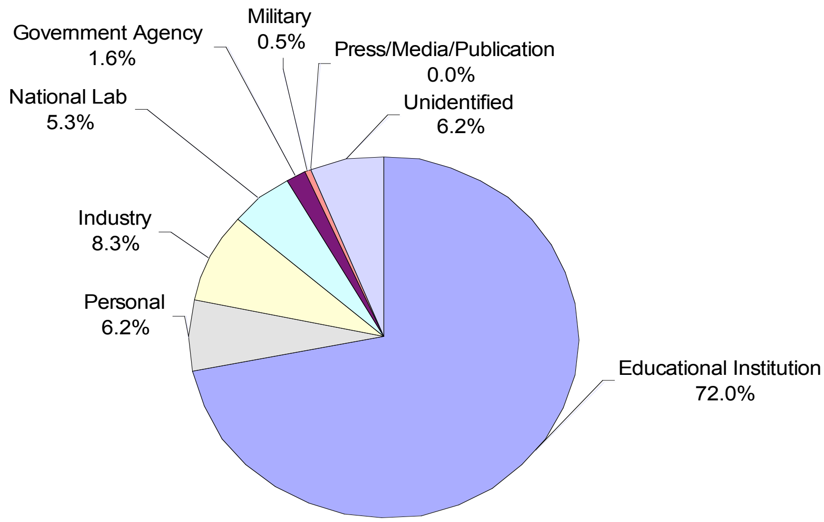


Source: SRI International and NCN's 4th Annual Report

The institutional affiliation of registered users conducting simulations using the NanoHUB infrastructure also points to increasing participation of non-academic users in NCN. Although academic users constitute the majority of simulation users, their share in the number of total simulation users has declined from over 90 percent in 2003-04 to about 72 percent in 2005-06.

Exhibit VII-8:

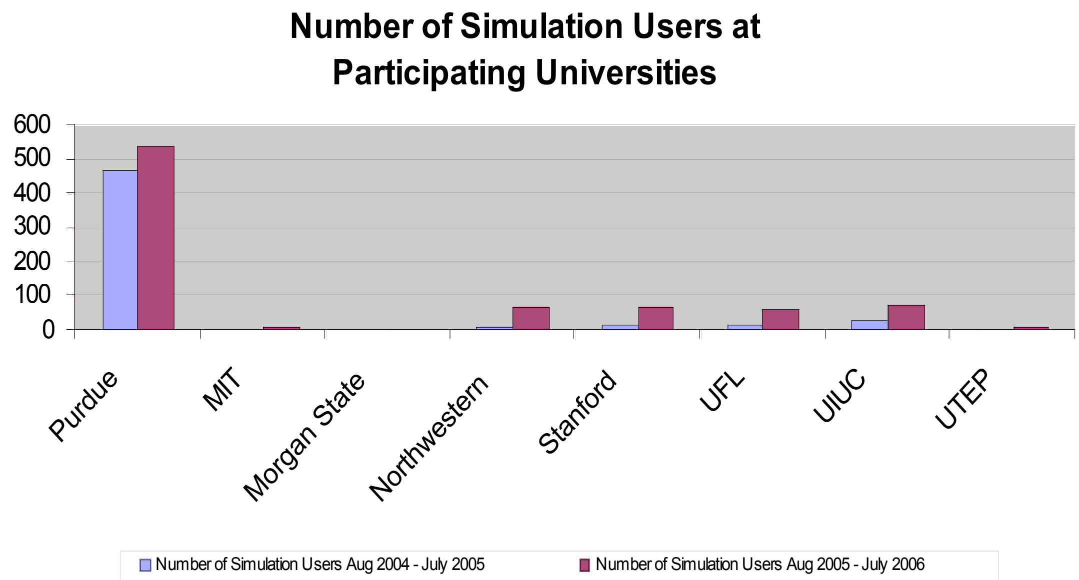
Number of Simulation Users, by Institution Type, August 2005 - July 2006



Source: SRI International and the NanoHUB Website (www.nanohub.org)

Among the academic simulation users, researchers from Purdue University have been the dominant users of NanoHUB resources. However, the share of node universities in simulation users has nearly tripled in just one year, rising from just 13 percent in 2004-05 to nearly 35 percent in 2005-06, indicating increasing adoption of simulation tools and algorithms by the nanoscale research community in node universities. Exhibit VII-9 presents share of participating universities among simulation users.

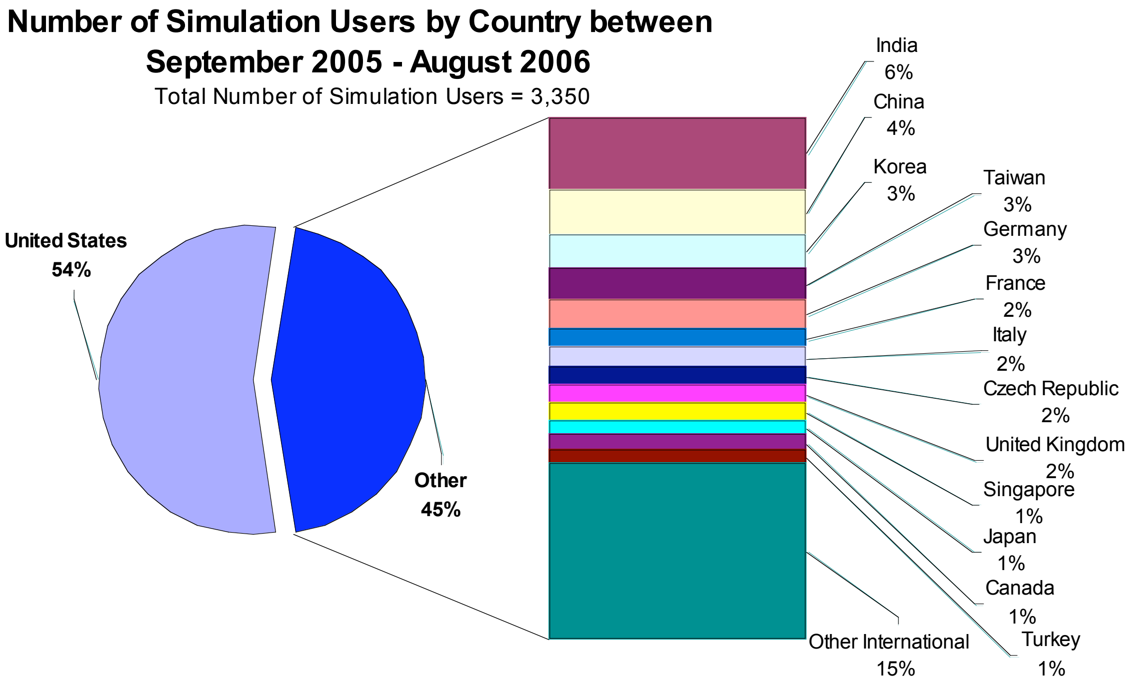
Exhibit VII-9



Source: SRI International and NanoHUB Website (www.nanohub.org)

While NCN is witnessing increasing adoption and use of NanoHUB's simulation resources among universities within the network, it is also growing in popularity among the global community of nanoscale researchers. As evidenced by the location of registered simulation users, users from outside of the United States constitute over 45 percent of all simulation users. Asian countries constitute over 20 percent of simulation users, with India, China, and Korea leading the list. Increasing awareness generated by the participation of NCN PIs in international conferences, seminars, and lectures is believed to be instrumental in the growth of the non-U.S. users of NanoHUB. By enabling access to a wide array of simulation resources and educational content, NCN is contributing to the development of a global community of nanoscience researchers.

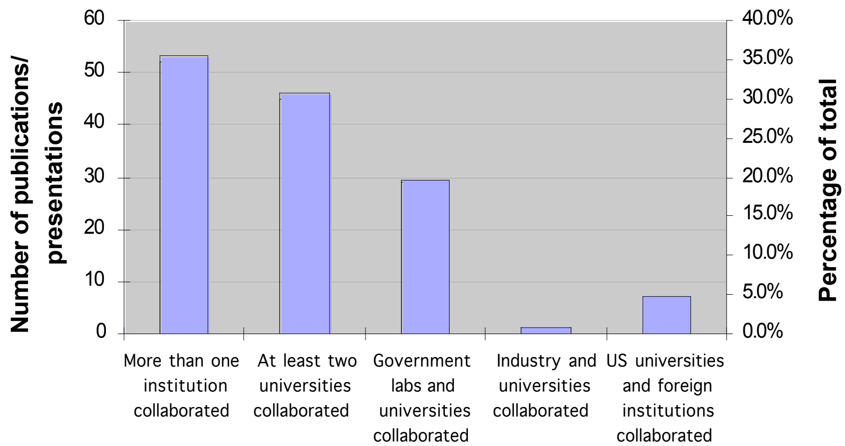
Exhibit VII-10:



Source: SRI International and NanoHUB Website (www.nanohub.org)

The collaborative design of the network leads to strong cooperation among researchers and resource developers within the network. An analysis of all NCN publications, conference proceedings, and presentations shows that in 2005, the average number of authors per publication was 4.61, up from 3.78 in 2004. Over 98 percent of all publications and presentations produced by NCN researchers were co-authored and nearly 40 percent were co-authored by more than four researchers. These authors represented a multitude of disciplines from a variety of academic institutions, government labs, and industry. In nearly 35 percent of all publications recorded in 2004 and 2005, authors from at least two different institutions had collaborated.

Exhibit VII-11:
Institutional Collaboration in all NCN Publications/ Presentations (2004-05)



Source: SRI International and NCN's 4th Annual Report

Researchers from U.S. universities had collaborated with their counterparts from government labs in at least 20 percent of all publications and with foreign researchers in nearly 5 percent of all publications. The number of publications co-authored by researchers from multiple institutions was on the rise through the life of NCN, with the exception of 2005-06.[30]

Economic Impact

We sought data on various indicators of economic development, including patents awarded, technologies licensed, and new companies started out of NCN research. However, the NCN does not track or report any of these indicators. NCN management indicated that, first of all, the NCN program is a young program, having completed its fourth year recently. Secondly, although NCN researchers conduct basic and applied research in areas such as nanoelectronics, NEMS/nanofluidics, and nanomedicine, the program's focus is on transformation of research findings into usable tools and algorithms, leading to the development and deployment of content, simulation tools, animations, and applications on the NanoHUB. As a result, patents are not considered a key indicator of program outcomes or success.

It is also important to note that until recently the NCN had taken an open source approach to software technology and middleware development. Hence, although much advanced software and many tools have been developed, an exclusive arrangement with the industry to license NCN software has not been pursued. Recently, NCN has started exploring opportunities for commercial application of software and technologies developed by NCN researchers, although data on commercial use of NCN technology are not available yet.

[30] The total number of NCN publications declined in 2005-06, consequently decreasing the number of co-authored publications. As mentioned earlier, the NCN's Administrative Director pointed to the NCN management's decision to apply stricter guidelines on what should be counted as an NCN publication as a key factor behind the decline in the count of total number of NCN publications, and the number of co-authored publications in 2005-06.

Although a crude indicator, cost savings to organizations using NCN resources may be used as a proxy for the economic impact of NCN on non-network organizations. In 2005-06, NCN spent nearly $4.24 million in resource development, deployment, and cyber test-beds to support simulations on the NanoHUB. While over 12,000 users took advantage of the educational content, over 2,300 users executed 61,495 simulation jobs on NanoHUB. Therefore, NCN's cost of developing and maintaining the cyberinfrastructure per simulation is roughly $68.91. Given that users from industry executed 1,693 simulations on NanoHUB, cost savings to industry may be roughly estimated at $116,664. However, if all users including users from industry outside of the eight NCN network institutions are considered, total cost savings to organizations outside of the network may be estimated at nearly $2.14 million.[31]

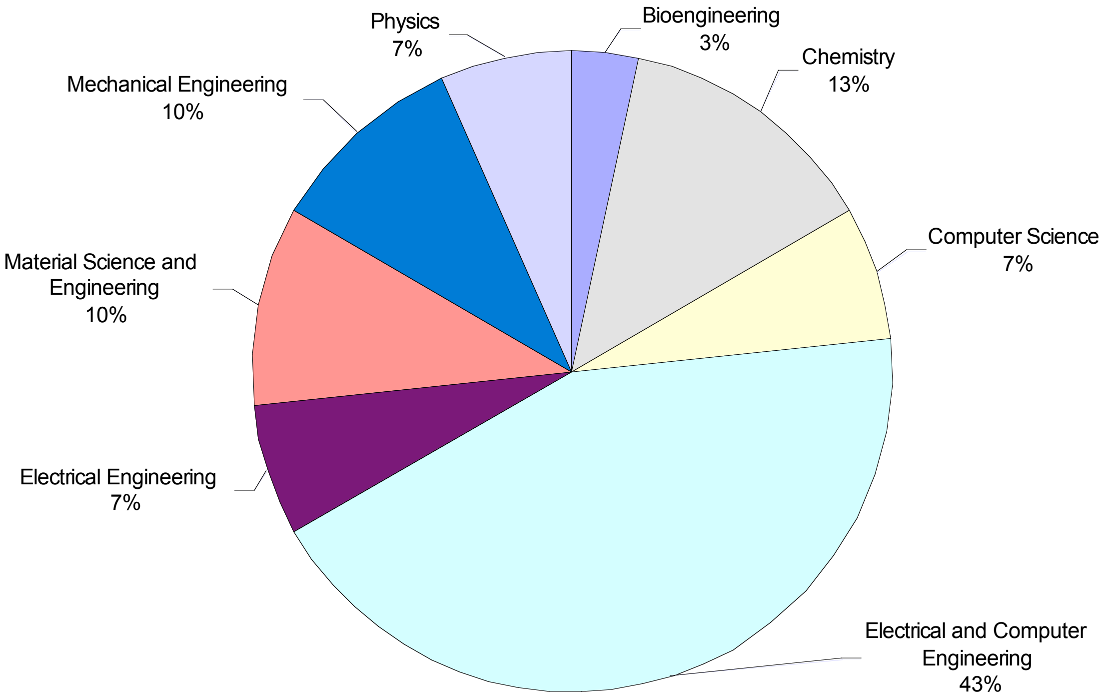
Interdisciplinarity

Interdisciplinarity is a core element of the NCN program. The 31 principal investigators of NCN represent eight academic disciplines: Bioengineering, Chemistry, Computer Science, Electrical and Computer Engineering, Electrical Engineering, Material Science and Engineering, Mechanical Engineering and Physics. Given the computational focus of the network, a majority of NCN PIs are affiliated with the Electrical and Computer Engineering and Computer Science discipline. Exhibit VII-12 presents the departmental affiliation of NCN PIs.

[31] Users outside of the eight network institutions executed 31,048 simulation jobs. With cost per simulation on the NCN infrastructure estimated at approximately $68.91, the total cost savings to these users may be estimated at $2.14 million. A more precise estimate of cost savings to external organizations could have been done if precise data on cost per simulation job were available. In the absence of such data, the estimates developed here are only indicative of NCN's potential impact on non-network organizations.

Exhibit VII-12:

Departmental Affiliation of NCN PIs

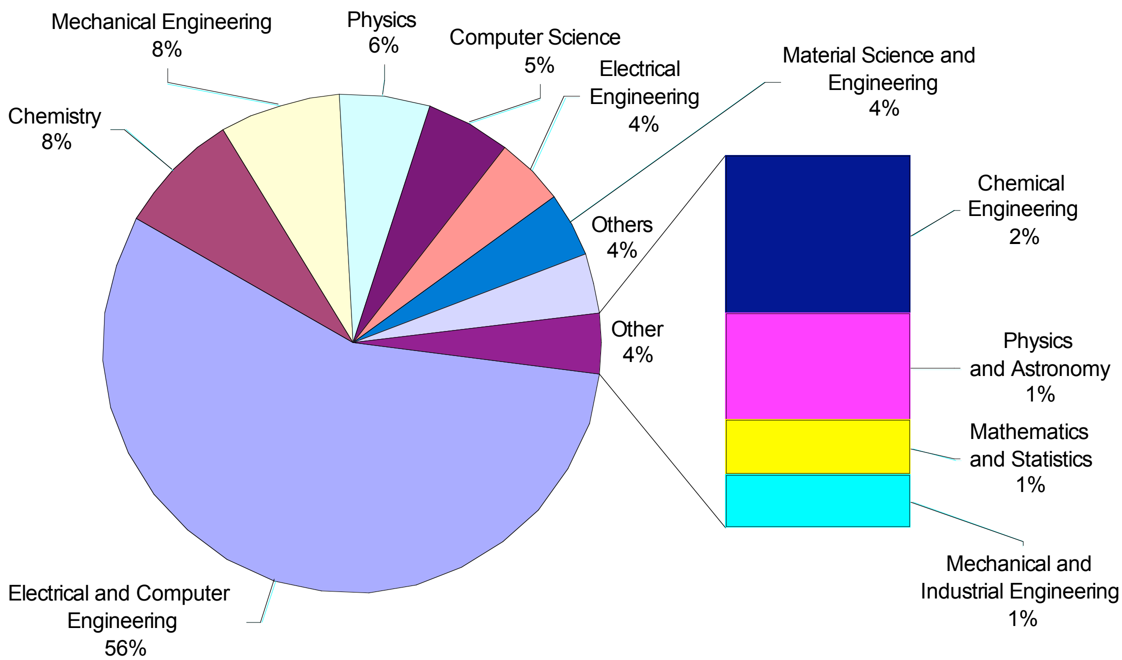


Source: SRI International, 2006

A high degree of interdisciplinarity is also observed among NCN researchers and collaborators who conduct joint research and co-author publications with NCN PIs. An analysis of the departmental affiliation of co-authors of NCN's publications and presentations in 2004 and 2005 shows that 12 academic disciplines were represented by co-authors of NCN publications and presentations. Electrical and Computer Engineering was the dominant discipline, representing 56 percent of all NCN publications during that period. Exhibit VII-13 presents a detailed breakdown of the disciplines represented by co-authors of NCN publications and presentations.

Exhibit VII-13:

Academic Departments of Co-authors of NCN Publications, 2004 and 2005

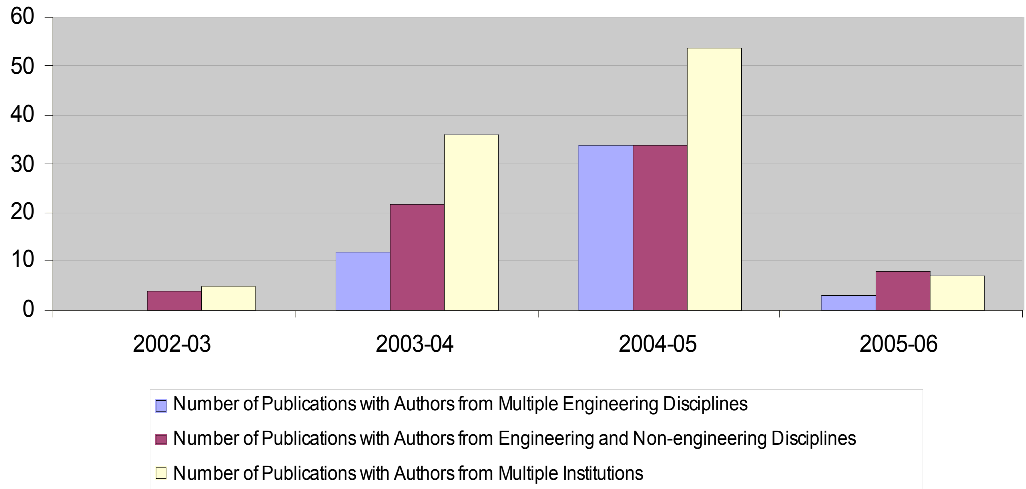


Source: SRI International, 2006

When publication trends are analyzed over the life of the NCN, further evidence emerges that supports the interdisciplinary character of NCN's activities. Since the inception of NCN, nearly 16 percent of all NCN publications in peer reviewed journals and conference proceedings have been authored by researchers from multiple engineering disciplines. Nearly 22 percent of all NCN publications in peer reviewed journals and conference proceedings have been authored by researchers from engineering disciplines in collaboration with their counterparts from non-engineering disciplines during the same period. In addition, as seen in Exhibit VII-14, with the exception of 2005-06 the number of publications co-authored by researchers from engineering disciplines or those between engineering and non-engineering disciplines has been on the rise.

Exhibit VII-14:

Trends in Coauthorship of NCN Publications



Source: SRI International and NCN's 4th Annual Report

It must be noted that data on the disciplinary affiliation of users who use and contribute to the development of NCN resources on the NanoHUB are unavailable at this time. NCN does not now collect such information from either registered simulation users or other users who do not run simulations or use any of the educational contents. In addition, disciplinary information on students, another significant set of NCN researchers and users, is also not available at this time.

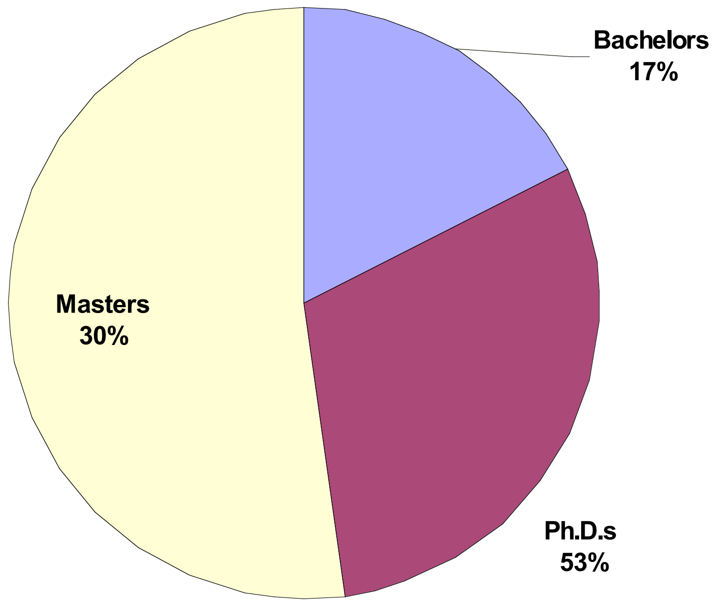
Education and Training

The NCN program engages undergraduate and graduate students through three major activities: research, resource development, and development and maintenance of the NanoHUB cyberinfrastructure. Between 2004 and 2006, 23 degrees have been granted to NCN students, of which 12 were Ph.D. students.[32]

[32] Table 1a (Quantifiable Outputs), p15, NCN's 4th Annual Report and Renewal Proposal to NSF, May 2006

Exhibit VII-15:

**Degrees Granted to NCN Students (2004-2006)
Total Degrees Granted = 23**



Source: SRI International and NCN's 4th Annual Report

The NCN program is supporting a large number of undergraduate and graduate students with varying degrees of financial support. These students contribute to NCN research or participate in curriculum development, resource deployment, and outreach. Exhibit VII-16 provides a breakdown of students currently engaged in and supported by NCN.[33]

Exhibit VII-16: Students Currently Supported by NCN

Students Currently Supported by NCN		
Degree Level	Research Activities	Curriculum Development and Outreach
Post Doctoral	7	2
Doctoral	68	4
Master	12	1
Undergraduate	2	6

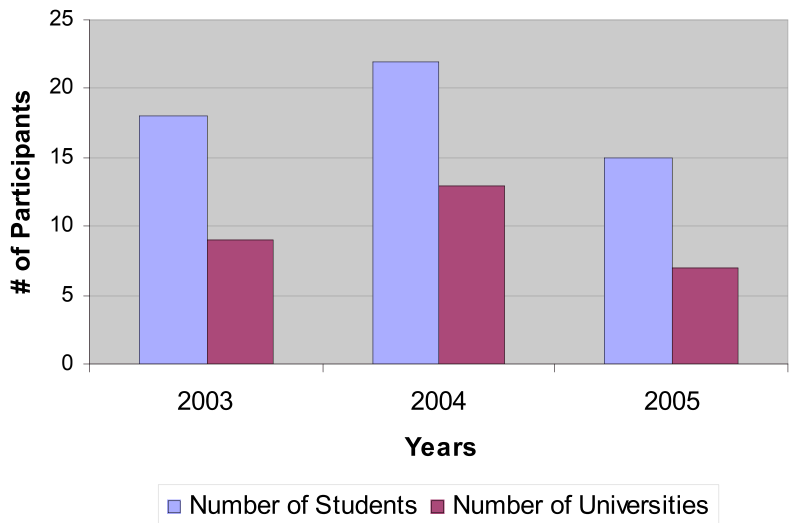
Source: NCN's 4th Annual Report

[33] SRI estimates based on data reported by the NCN in Table 2 (NCN Personnel) in the 4th Annual Report and Renewal Proposal to NSF, May 2006

The NCN also has supported 26 REU students, including students from the Summer Undergraduate Research Internship (SURI) program. NCN has jointly supported Purdue University's SURI program with the NASA-supported Institute for Nanoelectronics and Computing. Started in the summer of 2003, the SURI program has extended graduate research experience to 53 undergraduate students drawn from multiple universities. Of the 53 students who have participated in the SURI program, 35 have completed their undergraduate degrees, and 24 have subsequently enrolled in graduate studies in 14 premier universities. The following chart provides an annual breakdown of SURIs along with the number of participating universities.

Exhibit VII-17:

Summer Undergraduate Research Internship (SURI) Participants



Source: NCN's 4th Annual Report

Apart from the direct involvement of undergraduate and graduate students in NCN research and related activities, the NCN impacts education and outreach in nanotechnology through three primary sets of activities:

- **Educational impact through collaboration with other educational initiatives**: The NanoHUB team has played a key role in Supercomputing 2005 and 2006. The NCN team has held workshops and trained 30 teachers at the middle and high school levels. The NCN has established a partnership with the NSF-funded National Center for Learning and Teaching in Nanoscale Science and Engineering (NCLT) to utilize the NanoHUB to disseminate content presented in the NCLT seminar series. The NCN has also established a partnership with the newly formed NSF-funded Network for Informal Science Education (NISE) in Nanoscale Science, Engineering, and Technology, which is a group of 17 nationally-renowned science museums and over 200 agencies and organizations led by the Boston Museum of Science, the Minnesota Museum of Science and Technology, and the Exploratorium in San Francisco. NCN is working with TeacherTECH to make all NanoHUB content available to high school and middle school teachers participating in TeacherTECH.

- **Educational impact through curriculum development**: Courses developed by NCN faculty have been adopted in major research universities. The NCN PIs have developed 25 new courses, modified 20 courses and written two books that are being used by faculty and students in many undergraduate and graduate programs across the country.

- **Educational impact through workshops, conferences and seminars**: NCN uses workshops and seminars as a key means of knowledge dissemination. Since its establishment in 2002, NCN has organized 141 seminars and 51 workshops. Of the 51 workshops, eight were exclusively designed for researchers from industry. The NCN-supported Student Leadership Council (SLC)–an independent organization of NCN-affiliated students–hosts the Nanotechnology 501 Lecture Series on a weekly basis. The contents of the Nano 501 series are posted on the NanoHUB and have been viewed by 2,600 NanoHUB users from around the world.

Environmental, Health and Safety Implications

The NCN does not track environmental, health and safety implications of research. Accordingly, quantitative data on these impacts are not available, although the NCN program management acknowledges that NCN research may have long-term implications for the development and use of nanomedicine and nanodevices.

Societal and Ethical Implications

Although quantitative data on any societal impacts are not available, a major societal impact is foreseen in the development of a "virtual science community." As articulated by NCN's management, "the major social areas that will be impacted by the NCN program revolve around the concept of cyber-communities, the underlying infrastructure of the NCN program. The concepts of shared resources, from access to simulation codes to educational materials to collaboration facilities, are all focused towards building a community with a common culture and shared vision. The NanoHUB will be the model for how science, knowledge, and learning are disseminated in the future – a major change from the current research society."[34]

The NCN is not the only effort contributing to creation of a virtual science community. A variety of other cyberinfrastructure efforts around the nation have arisen since the formation of NCN, addressing the needs of scientists in various disciplines. Linked Environments for Atmospheric Discovery (LEAD), developed through NSF's ITR program, aims at building an

[34] Ned Howell, Managing Director of NCN, in an email response to SRI's question on societal implications of the NCN model of research and technology development and deployment, May 12, 2006.

infrastructure for forecasting episodes of severe weather. The National Virtual Observatory (NVO), also an ITR initiative, supplies survey data, analytic tools, and visualization facilities to astronomers. The new TeraGrid Science Gateways program is aimed at lowering barriers to access to theory, modeling and simulation resources. In the nanotechnology area, the European Union-funded Phantoms Nanotechnology Hub initiative acts as a repository of simulation codes useful for modeling and design of nanoscale electron devices. Yet, the NCN is unique in its focus on nanoscale level research in nanolectronics devices, NEMS, and nanomedicine, and in its creative approach to the rapid development and diffusion of knowledge in usable formats to a broad community of researchers around the world. NCN management believes that the NCN model can be replicated in other fields of science, and if that happens, NCN will have had a profound effect on the conduct of science.

VIII. Conclusion

This section summarizes the activities and outputs of two research and education support programs and two infrastructure support programs funded by the National Science Foundation as part of its contribution to the National Nanotechnology Initiative (NNI). These four activities were studied to document the extent to which they are meeting goals of knowledge transfer within the community of people and institutions interested in increasing the stock of knowledge in nanoscale science and engineering (NSE).

The activities have been designed to maximize possibilities for knowledge transfer. This includes opportunities in some cases for side-by-side collaboration among researchers at various levels of career development, interactions among researchers from different and diverse academic fields, and training opportunities for students and teachers. Virtual links are also made possible and encouraged through network applications and Web-based resources.

To gain as rich a picture of knowledge transfer as possible, data on six processes and outputs of each activity were collected:

- Research Outputs
- Collaboration
- Economic Impacts
- Interdisciplinarity
- Education and Training
- Societal, Ethical, Environmental, Health and Safety

Research Outputs

Publications in scholarly journals continue to be regarded as a primary indicator of knowledge flows within the research community. Both of the research and education programs we studied, NIRT and NSEC, have produced a high volume of scholarly output since their inception in 2001: NIRTs generated 1,086 total articles in peer reviewed technical journals and NSECs produced 1,822 total articles. By 2005, the final year of the 2001 cohort of NIRT awards, this set of 44 NIRTs was producing an average of nearly 26 articles per award annually—a level of output suggesting that the multiple co-PI's involved in NIRT awards have a substantial impact on research productivity as measured by publication output. NSECs also increased their publication output substantially each year of their existence: the 6 NSECs from the 2001 cohort, in their fifth year in 2005, were producing an average of nearly 75 articles per center, and the rate of increase showed no sign of declining. After four and five years of research activity for NIRT and NSEC awards, respectively, per-award publication outputs were continuing to increase.

Although the NanoHUB is the primary vehicle for knowledge transfer for NCN, NCN researchers produced 359 publications since the program's inception in 2002, and the annual production of papers is increasing. Despite the fact that the NNIN does not support research directly, users reported to NNIN staff that 1,734 papers published and presentations made in the period March 2004-July 2005 were related in some degree to research facilitated by the network. Across these four activities, there is clearly a substantial output of research-based knowledge, particularly remarkable because of the time required for newly-formed research teams to plan, organize, conduct research, and get results into print.

Collaboration

Collaboration, a key feature of NSE research and education programs, pervades the knowledge transfer processes and outputs we studied, taking a variety of forms and carried out at varying levels across them, but in all cases achieving substantial levels. The great majority of NIRT awards report collaborations with individuals or organizations; by their final year of operation, NIRTs averaged almost four organizational partners. For the 2005-2006 reporting year, most NSECs reported more than ten partnering institutions that participated in the planning and execution of the center. Typical partnering organizations for NIRTs are industrial firms and academic institutions, while individual collaborators typically are faculty members from other universities. The average number of collaborations increased steadily from year to year. In the case of NSECs, collaboration often takes the form of financial contributions in addition to research collaborations that do not involve the transfer of funds: 85 percent of the institutions that contributed to NSECs were in non-academic sectors. Industry collaborators were the most frequent among the non-academic group—the 14 NSECs report a total of 143 industrial partners. Notably, NSECs collaborated with 73 foreign institutions from both academic and non-academic sectors. Although cross-program comparisons should be treated with great care, NSECs appear to be at least as productive as Engineering Research Centers (ERCs); e.g., during 2005-2006 NSECs produced 50 articles per center while ERCs produced 30 articles.

The sharing of facilities, equipment and process information, and training that are integral to the two networks represent another form of collaboration. Currently nearly a third of NNIN users are from outside the host institutions; NNIN facilities and staff at node sites and on-line serve an average of 1,800 users each month from 11 different fields of science and engineering. More than 250 small businesses used NNIN facilities during March – December 2005. Although academic users constitute the majority of simulation users of the NCN, their share has declined from 90 percent in 2003-2004 to about 72 percent in 2005-2006, representing a strong infusion of industry resources. NCN users from outside the U.S. constitute more than 45 percent of all simulation users, with Asian countries constituting over 20 percent of all users.

Co-authorship of publications, across departments, universities, and sectors, is yet another indication of collaboration. Over their four-year reporting period, NIRTs report that between a third and half of their publication output is co-authored, although only a small proportion (a few percent) is co-authored with industry. Of the NSECs total output of 1,822 papers published in peer reviewed journals; just over 90 percent were co-authored. At least 89 percent of NNIN-related publications were co-authored, even though collaboration is not a primary goal of the sites. In the case of the NCN, over 98 percent of all publications and presentations produced by researchers were co-authored; in nearly 35 percent of publications recorded in 2004 and 2005, authors from at least two different institutions had collaborated.

Economic Impact

Economic impacts are a consequence of the value of research applications. Available indicators within the four activities studied suggest surprisingly strong potential for economic impact--surprising because the programs and awards have been in operation just a few years, and the commercialization of promising research results often takes many years. The activities of this type reviewed here indicate considerable technology transfer activity in the form of invention disclosures, patents, small business spin-offs, and licenses. In addition, we have calculated various measures of the economic value to supporters of these activities as rough indicators of their economic impact.

The totals for the several indicators of technology transfer activity across the activities are impressive. The numbers are probably conservative because neither NNIN nor NCN reports invention disclosures, patents, licenses, or spin-offs, although NNIN does report small firms "seeded" by reporting sites. NIRT and NSEC awards have generated 284 invention disclosures, 30 patents, and 12 licenses thus far. With government investment in NIRT and NSEC at around $170 million, this equals about $0.56 million per invention disclosure, a number well below the average cost of invention disclosures in U.S. research universities.[35] Including companies seeded by NNIN, the two research and education programs and the infrastructure award have generated 60 spin-off companies. The general pattern across indicators of economic impact for NIRT and NSEC is that that they increase over time as the programs mature, although this is not consistently the case.

Industry financial support for NSECs and expenditures for user fees for the infrastructure awards indicate economic value to industry. Industry support for NSECs for 2001-2005 totaled more than $15 million, averaging over $300,000 per center. NNIN users paid about $16 million in fees for the period March 2005-February 2006. Of this, industry paid more than $5 million, about two-thirds of this amount by small businesses. NNIN's cost of about $30 per lab user hour is low compared to costs of similar user facilities, indicating efficiency in providing access to infrastructure for the NSE research community. In the case of NCN, SRI estimated cost savings to organizations using NCN resources for the period 2005-2006 at nearly $2.4 million.

Interdisciplinarity

Interdisciplinarity is the phenomenon of knowledge transfer across traditional academic disciplines and established research fields. The concept of applying an interdisciplinary approach is built into the four activities studied based on the assumption that NSE is inherently interdisciplinary and outcomes will be enhanced by interaction. The four activities enable interdisciplinarity in different ways and manifest different indicators for each program. The different indicators we used converge, however, on a clear result: each of the four NSF activities

[35] A FY 2004 survey conducted by the Association of University Technology Managers reported that the average output was four invention disclosures for every 10 million dollars in research expenditures ($2.5 million per invention disclosure); the average output was 2.55 patent applications for every 10 million dollars in research expenditures ($4 million per patent application); and the average output was about one start-up company formed for every 100 million in research expenditures ($100 million per start-up).

studied shows, via multiple but largely suggestive indicators, considerable interdisciplinarity. To encourage interdisciplinary research, NIRT requires at least three co-PIs per award, up to a maximum of five. The average number of co-PIs over all NIRT awards is actually 4.27. More than 14 fields of science and engineering are represented by at least 1 percent of NIRT co-PIs, led by chemistry (20 percent), physics (16 percent), chemical engineering (15 percent), materials science and engineering (11 percent), and mechanical engineering (10 percent). The mean number of departments represented in the average NIRT award is 2.75, so the considerable departmental diversity sought for each award has been achieved. The departmental affiliations of senior researchers participating in NSECs are similarly diverse.

More than nine fields of science and engineering are represented by at least 3 percent of NSEC researchers, led by chemistry and chemical engineering (30 percent), physics (18 percent), mechanical engineering (13 percent), electrical engineering (9 percent), materials science (8 percent), and biology (8 percent). About 36 percent of participating researchers are affiliated with multiple departments, so interdisciplinarity is represented in both individuals and groups participating in NSECs. In a typical NSEC, participating researchers come from just over nine different departments, quite striking but indirect evidence of interdisciplinary research activity.

In the case of the NNIN, data are not collected in the same way as the two previously-discussed activities, but some interdisciplinarity can be assumed to be an outcome of interactions involving research. Data from NNIN sites for the last full year for which data are available show that network users are spread among 11 fields of science and engineering, led by materials research (21 percent), MEMS/mechanical engineering (17 percent), electronics (14 percent), optics (10 percent), and physics (10 percent). Using hours of use as an indicator of the diversity of fields using NNIN facilities shows a slightly different pattern, with MEMS/mechanical engineering dominating, followed by electronics, materials research, and optics.

Data on the disciplinary affiliations of the 31 principal investigators of NCN were available, broken into eight categories. Not surprisingly, given the computational focus of the network, just over 40 percent of the PIs are from electrical and computer engineering, and another 7 percent from computer science. Other fields represented among the PIs are spread relatively uniformly: chemistry (13 percent), mechanical engineering (10 percent), materials science and engineering (10 percent), physics (7 percent), and electrical engineering (7 percent). The publication output from NCN researchers and collaborators is similarly reflective of a wide variety of disciplines among co-authored works; the pattern is quite similar to the affiliations of the PIs just described. Since the inception of NCN in 2002, nearly 16 percent of all NCN publications in peer reviewed journals and conference proceedings were authored by researchers from multiple engineering disciplines, and nearly 22 percent were authored by researchers from engineering disciplines in co-authorship with researchers from non-engineering disciplines.

Education and Training

Education and training are knowledge transfer functions that, within the four activities studied, include formal involvement of undergraduates and graduate students in research, resulting in degrees granted; curriculum development, resulting in new courses, degree programs, and certificates; outreach to students and teachers in K-12 and to the general public; workshops, conferences, and seminars to academia and industry; and training of users seeking access to facilities and networks supported by the awards.

Of the 210 NIRT awards made between 2001 and 2004, the 189 that SRI tabulated have produced 195 Doctorates, 128 Masters, and 136 Bachelors degrees. The first cohort of 44 NIRTs, funded in 2001, has involved an increasing number of graduate students each year. The 14 NSECs were similarly productive over about the same period, producing 148 Doctorates, 57 Masters, and 53 Bachelors degrees. Between 2004 and 2006, the only years for which data are available, NCN students earned 23 degrees, of which 12 were Doctorates. More than 3,200 graduate students conduct research at NNIN member institutions per year, and more than 1,000 Doctorates are awarded each year in which research using NNIN facilities plays a part; the data do not permit us to identify what proportion of these students are "NNIN students" in the same sense that there are program criteria for identifying NIRT, NSEC, and NCN students.

Half the NIRT awards produced at least one contribution to curricula. A total of 194 contributions were reported, or just over two per award among the awards that contributed to new curricula. NSECs produced 154 new courses based on their research, and were responsible for three new degree programs, five minors, and five certificate programs related to nano. NCN PIs have developed 25 new courses and modified 20 other courses. The NNIN education portal on the main NNIN Website, launched in 2005, is the primary focus for the network's educational efforts. The site will be the repository for training materials, lesson plans, and activities developed by NNIN sites. The Website also provides access to lectures on nanotechnology, graduate-level discussions related to specific disciplines, lectures related to mentoring, and instructional material related to social and ethical considerations in nanotechnology.

Approximately one-third of the NIRT awards report giving at least one workshop or short course related to their research. A total of 61 were provided to industry audiences, with the remaining 178 given to other types of audiences. NSECs offered 739 workshops and short courses, 3,655 seminars and colloquia, and ten courses on the Web. The network awards obviously have unique resources available to realize their education and training objectives, and they are taking full advantage of them. NCN, working through its NanoHUB, is disseminating content presented at the NSF-funded National Center for Learning and Teaching (NCLT) in nanoscale science and engineering. NCN is partnering with the Network for Informal Science Education (NISE) in Nanoscale Science, Engineering, and Technology, a group of 17 science museums and over 200 other agencies and organizations. Since 2002, NCN has organized 141 seminars and 51 workshops, eight of which were exclusively for industry. Each of the NNIN's 4,140 annual users is trained in the use of multiple instruments and techniques, usually in a hands-on, face-to-face manner. More than 700 people attended workshops during 2005-2006. Many NNIN sites run programs such as chip-camps that provide educational experiences for middle and high school students. From NNIN site reports on these activities, it is clear that thousands of people have participated in NNIN outreach activities.

Environmental, Health and Safety Implications

The environmental, health, and safety implications of NSE are explored as parts of these four activities. Activities that have laboratories provide training in laboratory safety. For example, each new user of NNIN (numbering 1,680 in 2005-2006) receives extensive health and safety training prior to use of the facilities. This initial training averages four hours per user, or more than 6,700 hours of training.

Societal and Ethical Implications

Each of the four activities to some degree considers the societal and ethical implications of NSE research. NSEC took part in forming the Center for Nanotechnology in Society, a program with four nodes, each with a specific focus on societal and ethical implications of NSE. Four of the NNIN network sites--Cornell, Stanford, Washington and Georgia Tech--are leading NNIN planning and initial implementation of research and education, training and development, and outreach focused on the societal implications of nanotechnology development and application.

Overview

The two research and education programs and two infrastructure awards studied for this report provide overlapping and complementary forms of knowledge transfer to a variety of user groups. The NIRTs and NSECs emphasize research involvement and education of undergraduates and graduate students, using more traditional methods of knowledge transfer: classroom learning and laboratory experience under the guidance of mentors. The two infrastructure support awards have different primary audiences, appropriate to the resources available to each. NCN offers access to unique resources for academic and industrial users, with support from and interaction with the staff at each network site providing considerable transfer of knowledge and know-how. Workshops, seminars, and short courses are key mechanisms of transfer for both NCN and NNIN. Both network awards emphasize outreach to the public, K-12 students, and teachers, complementing the awards programs' relative emphasis on students and researchers in higher education settings.