Assessment of Fifteen Nanotechnology Science and Engineering Centers' (NSECs) Outcomes and Impacts: Their contribution to NNI Objectives and Goals

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Final Report
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NSEC Assessment of Outcomes and Impacts
Final Report Outline

Introduction

This project focuses on the assessment of outcomes and impacts of fifteen of the Nanoscale Science and Engineering Centers (NSECs) funded by NSF. The purpose is to understand the mechanisms by which this collection of centers contributes to the realization of the goals of the National Nanotechnology Initiative (NNI), namely:

1. Advance world-class nanotechnology R&D
2. Foster the transfer of new technologies into products for commercial and public benefit
3. Develop and sustain educational resources, a skilled workforce, and supporting infrastructure to advance nanotechnology
4. Support responsible development of nanotechnology

The assessment is focused on the program level so we do not report on all the activities of individual centers. Rather, the report is organized around the main areas in which collective patterns of impact have been detected. The evidence used to draw our conclusions includes not only what is available from the centers themselves, but also data at the nanoscale science and engineering (NSE) field level to situate the centers in the entire field in order to gauge the outcomes of the program on the development of the NSE domain. This is in line with the intent of goal #1 of the NNI that, if fulfilled, should lead to a directly measurable impact on the entire field of nanoscale science and technology. We are also able to gauge some of the contributions of the program to goals #2 and #3 with these data, though a better understanding of these and outcomes related to goal #4 will emerge from our combined quantitative-qualitative analysis.

Methodology and Data

a. Methods

The approach is a mixed method quantitative-qualitative design widely used in evaluation. Publication, citation, personnel, funding and other available quantitative data for nano centers were gathered. From the analysis and interpretation of these data, we designed and conducted a qualitative component consisting of three in depth case studies and interviews of center PIs.

The design has two main research operations stages and a final data analysis stage:

1. Quantitative analysis of available data on nano research centers and the nano field.
2. Qualitative case studies of centers designed with the results of the quantitative analysis to provide in-depth explanations of the role of centers in the nano field.
3. Semi-structured interviews of all center PIs.
4. Analysis of combined, quantitative and qualitative data.

The data were obtained from the following sources and activities:

- Acquisition of 85 center annual reports from all 15 NSEC centers
- Extraction and clean up (duplicate removal) of publication lists
- Extraction of NSEC articles from Web of Science (n=3,500) for comparison and determination of a uniform data set across centers
- Look up and extraction of articles citing NSEC articles (n=75,000)
- Clean up and classification of collaborating organizations from reports and interview data
- Clean up, look up, identification, and matching of NSEC authors in author listings

For our quantitative analyses and interpretation we used several tools:

- Growth, shares, and overall trends (spreadsheets and tables)
- Networks and collaborations (Gephi)
- Geographical spread, GIS (ArcGIS)

- Keywords and topics (VantagePoint)
- Multidisciplinarity and science maps (Pajek)
- Citation analysis (Own code developed in R)

Research Performance and Impact on the Field

Most of the evidence of the contribution of the NSEC program to the first goal of the NNI, namely, the advancement of world class nanotechnology R&D, is related to the publication record of the researchers at the centers and the impact measured by citations. These are certainly not the only measures of quality and impact, but they are the most readily available and an unavoidable reference in the scientific community. In this section, we document the publication productivity and its impact and use information from a database containing all the publications in the field since 1991, as defined by Porter et al. (2008).[1]

b. Publications and citations

The evolution of publication output of the centers shows steady growth over the life of the program, showing two composite dynamics (Figure 1). On the one hand, the growth reflects the results of the research activity in the centers that gained momentum over the first few years of the life of each center to the point where they produced research results at a maximum capacity level. On the other hand, centers were created in several stages, adding total capacity to the program, which contributed to continuous growth in output until very recently as the last centers came online and gained momentum. The last period in the figure shows incomplete information, not a decline in production. This is due to the delay in the capture of publications and citations by the main public databases. In sum, with the addition of capacity with new centers, the output shows steady growth, indicating that the center program is a healthy system of scientific activity. All research programs hosted by centers were able to gain momentum and contribute publications that were sufficiently worthy to be published in journals selected for cataloguing in the Web of Science and other databases of scientific articles.

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[1] Porter, A., Youtie, J., Shapira, P., Schoeneck, D. (2008). “Refining Search Terms for Nanotechnology,” *Journal of Nanoparticle Research,* 10(5):715-728.

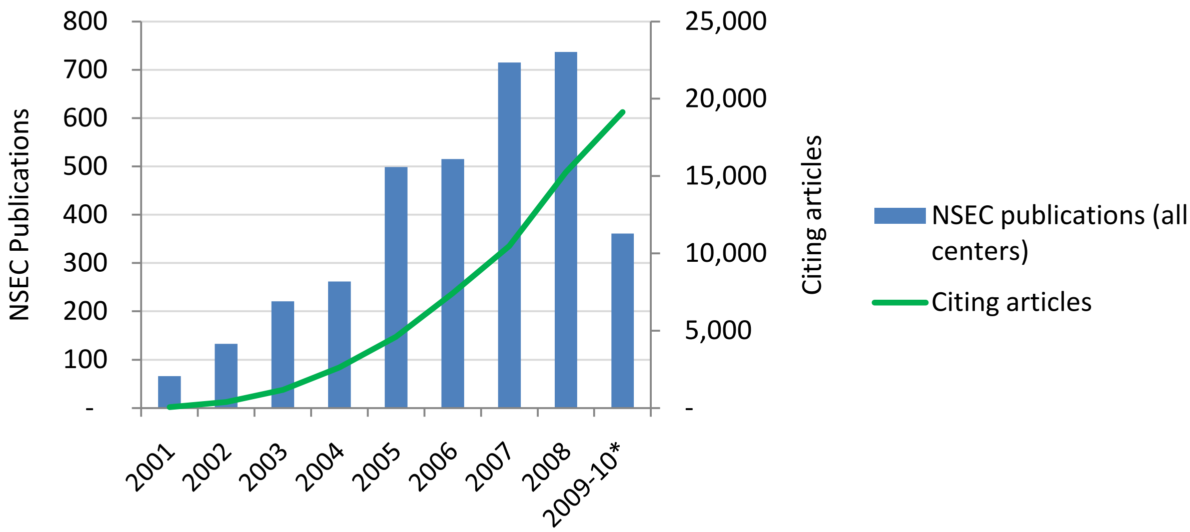


Figure 1. NSEC Publication Activity and Citations

The numerical values used in the construction of the graph in figure 1 are shown in table 1.

	2001	2002	2003	2004	2005	2006	2007	2008	2009-10*	2001-10*
NSEC publications (all centers)	66	133	221	262	499	515	715	737	361	3,870
▪ *Annual change*		*102%*	*66%*	*19%*	*90%*	*3%*	*39%*	*3%*	*-51%*	*34%*
Citing articles	48	391	1,164	2,619	4,595	7,415	10,469	15,243	19,149	94,484
▪ *Annual change*		*715%*	*198%*	*125%*	*75%*	*61%*	*41%*	*46%*	*26%*	*12%*

Table 1. NSEC Publication and Citation Counts

Notes to Figure 1 and Table 1: *Publication data not reported by all NSEC centers; last column reports average annual change for rows with change data.

Source: ISI-WoS publication data based on NSEC annual reports by center.

i. Field level assessment through citations

A sense of the impact of the NSECs on the entire field can be obtained through comparing the citation performance of the first cohort of centers to the field using the nanotechnology publication data for the entire field. Using data for the cohorts of 2001 and 2002, which represent the first two years of publications of the first centers that were funded by the program and the cohorts for the same years for the entire field we find that the centers take a leading role in the field from the very beginning. The data are shown in tables 2 to 4.

NSEC papers in both cohorts rank highly in the field. The median number of citations to NSEC papers almost doubles the field average at each window length and the average almost triples the field average for the 2001 cohort. The median more than triples the field's median, with the average almost four times larger, at each window length for the 2002 cohort. In other words, the collection of papers produced by centers as a group are at the top of the field as a whole, as measured by citations.

	2001	2002	2003	2004	2005	2006	2007	2008	2009
N_Mean	0.88	6.30	14.44	23.64	35.88	48.48	61.11	75.61	90.17
N_Med	0	2	4	6	9.5	11	12.5	14.5	17.5
N_Max	12	52	148	297	528	776	1062	1409	1760
F_Mean	0.26	2.11	5.13	8.18	11.62	14.78	17.87	21.11	24.04
F_Medi	0	1	2	4	5	6	8	9	10
F_Max	39	163	376	747	1268	1803	2286	2902	3484

Table 2. Citation statistics for the NSECs (N) and the field (F) cohort 2001

Note: Total Cohort 2001: 30462 papers. NSEC Cohort 2001: 66 papers.

	2002	2003	2004	2005	2006	2007	2008	2009
N_Mean	1.20	9.06	21.32	36.92	51.75	67.13	85.15	101.80
N_Med	0	3	8.5	16	20.5	25.5	30.5	36.5
N_Max	19	88	196	400	585	807	1063	1330
F_Mean	0.28	2.32	5.30	8.83	12.10	15.36	18.79	21.92
F_Med	0	1	2	4	6	7	8	9
F_Max	50	153	340	661	1053	1499	2042	2587

Table 3: Citation statistics for the NSECs (N) and the field (F) cohort 2002

Note: Total Cohort 2002: 34971 papers. NSEC Cohort 2002: 128 papers

If we look at individual papers for influence on the field by following the most highly ranked papers in each cohort, we find that the top 20 most highly cited papers of the two cohorts are among the most highly cited papers in the field. The 2002 cohort shows a trend that will consolidate with the evolution of the program, namely, that the influence of NSEC papers grows with time. The top-cited 2001 paper currently is the 5th most cited paper of all 35,000 published in 2001 (as captured by the Georgia Tech nano-search). The top 20 NSEC papers are among the top 566 papers of the almost 35,000 published in the field, and two of its papers are in the top 10 of the entire field (table 4b). We must note that this is also an indication of early influence since these cohorts are the first two cohorts of the entire program when only a few centers were in existence.

	1	2	3	4	5	6	7	8	9	10
2001	5	29	98	167	179	223	313	411	465	629
2002	6	10	17	20	23	56	69	124	127	148

Table 4a: Rank of the top 10 NSEC papers in the field of Nanotechnology

	11	12	13	14	15	16	17	18	19	20
2001	834	1345	1383	2077	2992	3202	3203	3283	3284	3755
2002	175	192	228	279	322	382	430	513	559	566

Table 4b: Rank of the 11th to 20th ranked NSEC papers in the field of Nanotechnology

To add to the evidence for the influence of the NSECs on the entire field we also note that speed at which the number of citations grows is very high. We expect the number of citations to grow faster than the number of published papers since the average citations per paper is greater than 1. However, the speed at which the number of citations grows is a good scale-free measure of the performance of a unit if compared to a field. On average, NSECs have a cumulative number of citations that grows exponentially with exponent 2.22 (standard error of0.14). This means that when the number of published papers doubles, the number of citations grows by a factor of 4.66. As a matter of fact, due to the shortening window for the count of citations, this is a lower bound for the growth rate of citations.

ii. Assessment using journal quality measures

Another impression of the impact of scholarly activity can be obtained from the analysis of citations at the journal level to assess the quality of the journals in which center authors publish. In order to illustrate the dynamics of the influence of NSEC publications by tracking the quality of the journals in which research papers appear, we have selected two centers, one from the first cohort and one from the second, and compile the journal impact factors for their publications in each year.

The exact details of the distribution of impact factors for each center will show field effects since dominant journals in subfields have impact factors that depend on the subfield size and growth rate of the papers published in it. Features of the distributions are also tabulated below. Journal Impact Factor (JIF) represents the frequency with which the “average article” in a journal has been cited in the most recent two-year period.

The first center belongs in an earlier cohort and has been in existence for a decade. Figure 2 shows the frequency distribution for 2008 JIF for the center’s publications.[2] The average JIF for the period 2000-2008 is 5.36 and the median JIF is 3.05. The range of impact factors is 0.16 to 31.4.

The impact of centers’ publications grows in time as the research program consolidates. Figure 3 shows that papers of Center #1 have been increasingly placed in prestigious journals over time using two year intervals to show the evolution to keep the presentation compact. In 2002 (left bottom panel), only one paper was published in journals with JIF more than 10.

[2] Journals without ISSN numbers are not included in this analysis (such journals are typically lesser impact journals).

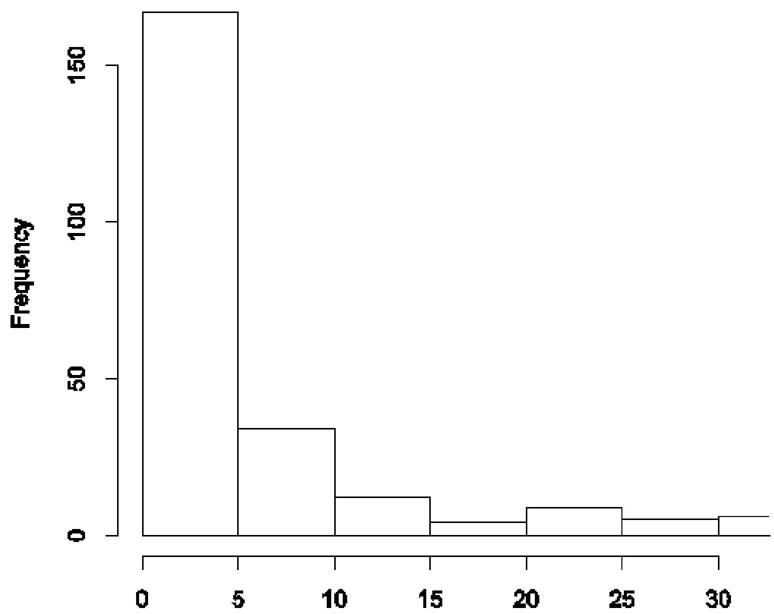


Figure 2. Frequency distribution of JIF for papers of Center #1 (2002-2008)

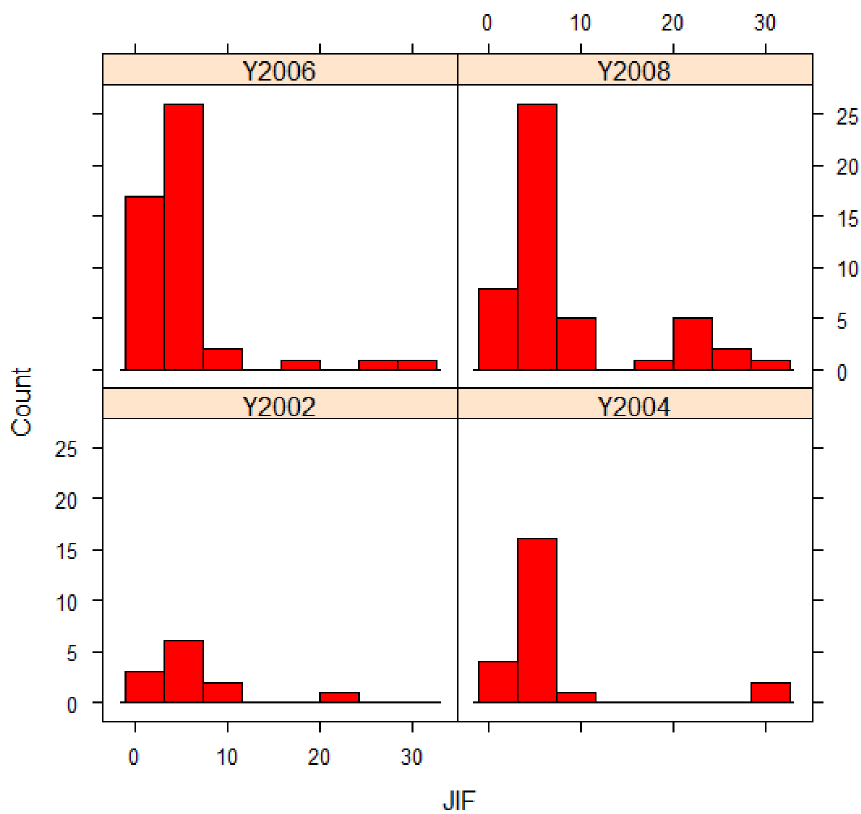


Figure 3. Journal Impact Factors by year for Center #1

In 2008 (upper right panel), over 8% of the papers were accepted in journals with JIF greater than 10 and 4.5% of papers were in the very select journals *Science* or *Nature.* Table 5 summarizes the data for this center.

Avg. JIF[3]	6.3
Median JIF	3.7
Range of JIF	0.16-31.4
% of papers published in Nature/Science	4.5%
% of papers with JIF>1	97.9%
Avg. TC	35.5
Median TC	14
% of papers with cites>0	93.5%

Table 5. Indicators of Research Impact for Center #1

About 5,750 research articles have cited this center's publications between 2002 and 2010.[4] Since the windows are longer, the number of papers with at least one citation is greater: 93.5%.

In order to show this pattern, which is typical of the centers in the program, the same information is developed for a center from a newer cohort that began publishing in 2006. The result is very similar and the growing influence of the publications resulting from the research program of the center can be clearly perceived. The JIF for the center's publications has the same range as the previous center, the distribution of JIF's of the journals in which the center's publications appear has an identical shape and analogous evolution of the impact factors in time. Given that this center has been in existence for a much shorter period, the four graphs showing the evolution of impact factors belong to consecutive years. Together with the growth in the number of papers as the center's research program gains momentum, the growth in the number of papers on the right tail of the impact factor axis is clearly noticeable, not only in number, but also shifting further to the right with the increase in impact factor.

[3] 2008 journal impact factor is used as a reference.
[4] Only citing articles until February 17th, 2010 are included in this analysis.

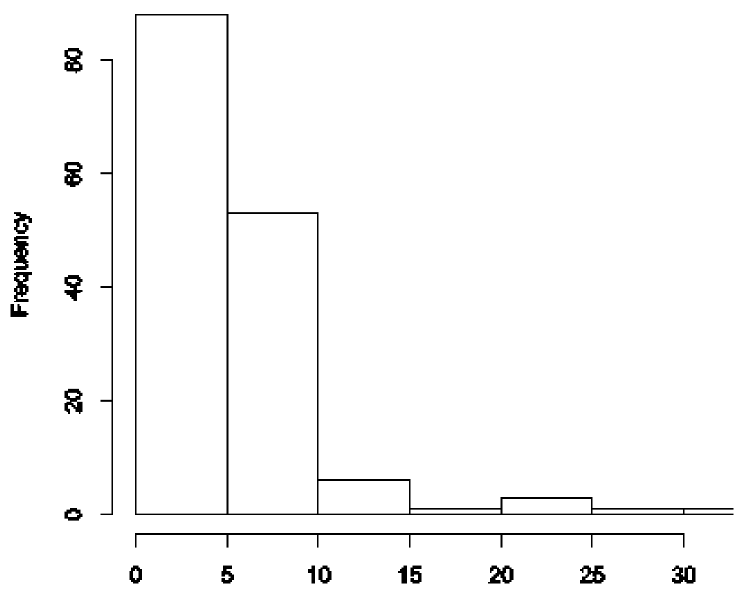


Figure 4. Frequency distribution of JIF for papers of Center #2 (2006-2009)

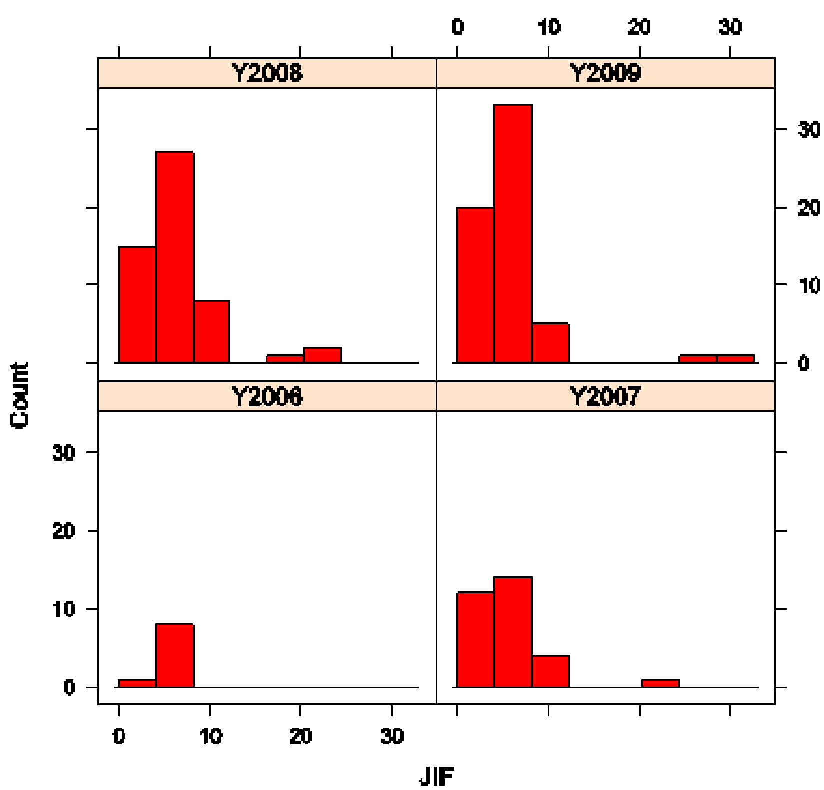


Figure 5. Journal Impact Factors by year for Center #2

Avg. JIF[5]	5.66
Median JIF	4.6
Range of JIF	1.2-31.4
% of paper published in Nature/Science	3.67
% of paper with JIF>1	100%
Avg. # of citations	5.47
Median # of citations	2
% of paper with cites>0	68%

Table 6. Indicators of Research Impact for Center #2

Table 6 shows that all papers associated with this center were published in journals with an impact factor greater than 1. The average journal impact factor for the center's publications is 5.66 while the median is 4.6. Six papers were published in either *Nature* or *Science*. The average number of citations as of March 2010 is 5.47. More than two-thirds of the papers have been cited at least once. Of course, the time windows are rather short since the center begins to gain momentum from its second or third year which leaves very little time for citations to accumulate and, despite the widespread belief in early citations, our own studies of nanotechnology publications show that there are many important papers in nanotechnology that take several years to accumulate important numbers of citations.[6]

c. Co-authorships and collaboration

The influence of the centers' research on the overall field of nanotechnology can also be gauged from the patterns of collaboration that are observed from the co-authorship of research publications. In the first place, the sheer volume of collaborations reflected in the co-authorship patterns over the life of the program is truly remarkable. Figure 6

[5] 2008 journal impact factor is used as a reference.

[6] Rogers, J. (2010). "Citation Analysis of Nanotechnology at the Field Level: Implications for R&D Evaluation," *Research Evaluation*, Vol. 19, No. 4, pp. 281-290.

contains a complete network map of co-authorships. Each node in this network represents an author. Each edge represents an instance of co-authorship between the two individuals and the size of the node represents the number of publications by that author. The edges are color coded to represent a center in which the publication is counted.

Three particular collaboration phenomena emerge from the observation of this network. First, there are networks of several highly productive authors that are also highly collaborative, reflecting the creation of a critical mass in key areas of nanotechnology research. Second, a number of highly productive authors become central to a wide network of collaborations that extend beyond the center itself. This shows how research conducted in other places becomes interdependent with the centers and their leadership in the field. Third, there are some clusters containing a large number of authors that are connected; these are related to projects that require the involvement of many people. This reflects the ability of the centers to concentrate and coordinate efforts of many researchers on projects that would not be feasible without this infrastructure. These patterns are observed in Figure 6 and highlighted with the augmented boxes.

When the network of co-authorship is observed over time, the catalytic effect of the work of centers is reflected in the diversification of collaboration. Figure 7 shows the same co-authorship network for all the centers in the program containing publications of two non-overlapping periods. Some of the small groups of rather isolated authors on the periphery of the networks are shown to grow and increase their connectivity indicating that new collaborations are emerging in diverse areas amongst authors who are not part of the most densely connected parts of the existing co-authorship network.

NSEC collaboration networks present diverse patterns of co-authorship
(2001-2010)

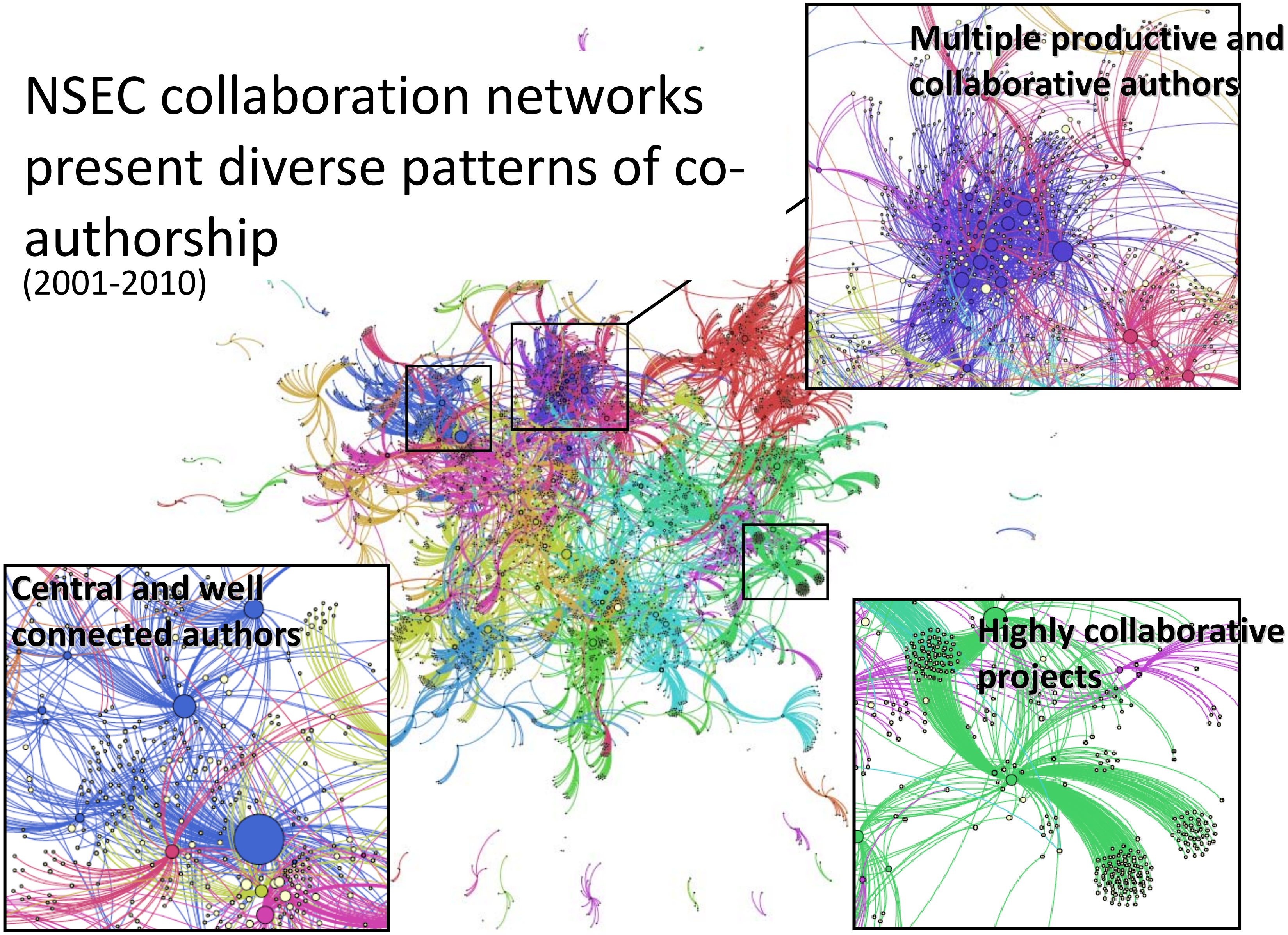
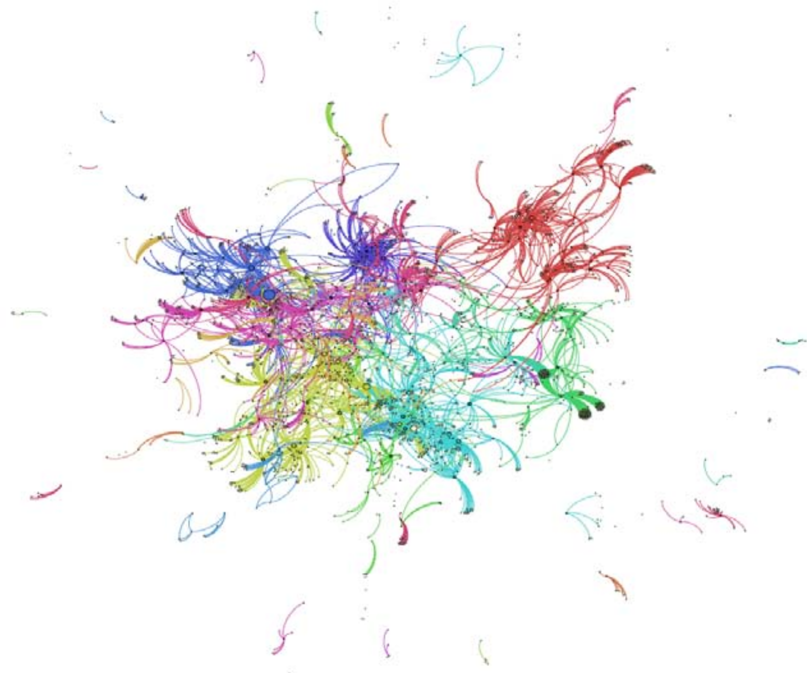


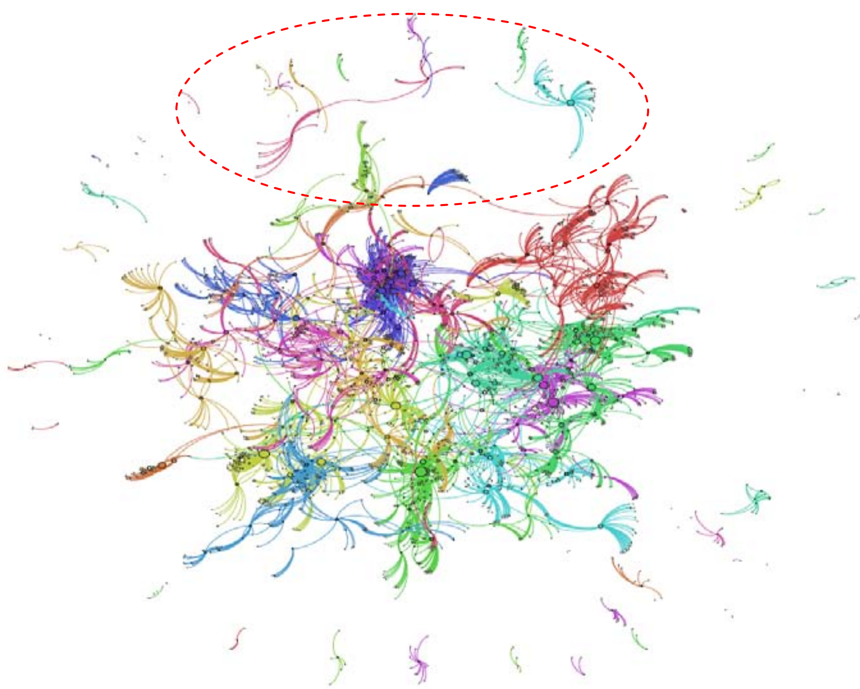
Figure 6. Diverse patterns of collaboration in the co-authorship network

Figure 7. NSEC co-authorship networks grow and become more widespread

Co-authorships 2001-2006



Co-authorships 2007-2010



Notes: Nodes represent authors. Node size represents number of publications for the period. Node colors represent 15 NSEC centers. Line colors extending from a center's nodes indicate co-authoring with researchers not themselves affiliated with the center.

Source: ISI-WoS publication data based on NSEC annual reports by center.

i. Geographical distribution of collaboration and impact

The influence of program centers' work can also be gauged geographically. Center researchers collaborate with colleagues across the United States and across the world. Their papers are also cited by researchers virtually in all the countries where nanotechnology R&D is conducted. Figure 8 shows the distribution of publications by center researchers and their co-authors and the location of papers that cite them. Most of the co-authors are in the United States, but if close attention is paid to the colored circles representing location and number of papers at the location, there are several darker circles outside the United States, mainly in China and Europe, representing foreign co-authors. The circles in the lighter color represent citing articles and they are massively present across the world, showing the strong presence of program supported nanotechnology research in the world, including in countries such as Africa and South America that have not been prominent in nanotechnology research.

The centers indirectly support nanotechnology across the United States by engaging widely in collaborations with researchers in almost all the states of the Union. Figure 9 shows in dark colored circles the location of co-authors of center papers. The centers have collaborated with researchers in all but 4 of the states in the country. They are cited in all states. This is a good indication of the broad geographical influence of center activity. Even though it is not a strict measure of scientific quality, it is certainly an indirect one since it shows that the scientific community of the field as a whole seeks out center researchers for collaboration and catalyzing of their own work. In terms of the nature of the impact of the investment in the program, it shows a pattern of generous "spillovers" (positive externalities) that benefits the entire field.

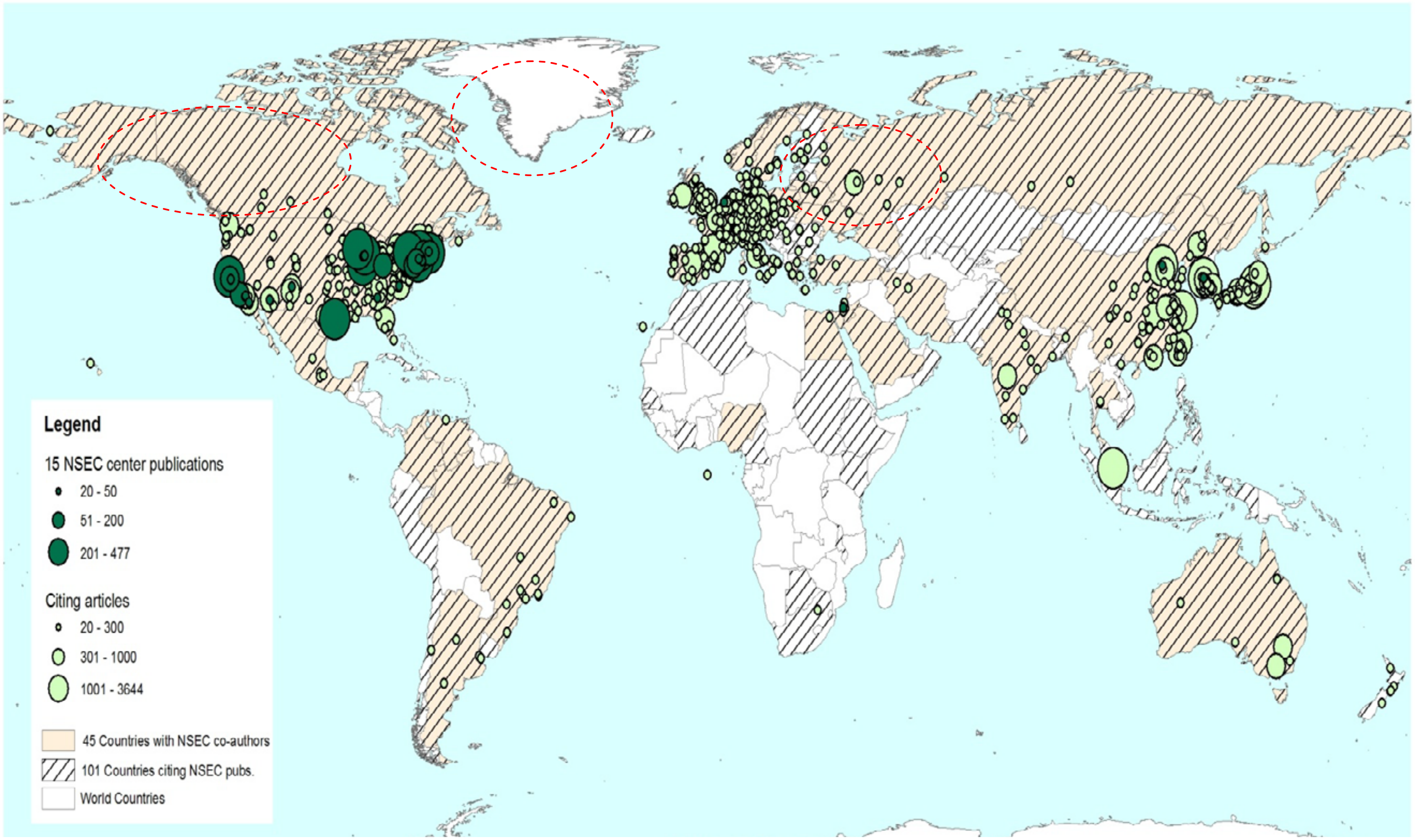


Figure 8: Geographical distribution across the world of center publications and citing articles

Note: Number of NSEC publications from 2001-2010 = 3509; number of citing publications = 75335. Citing publications, 2001-2010 exclude all NSEC publications.

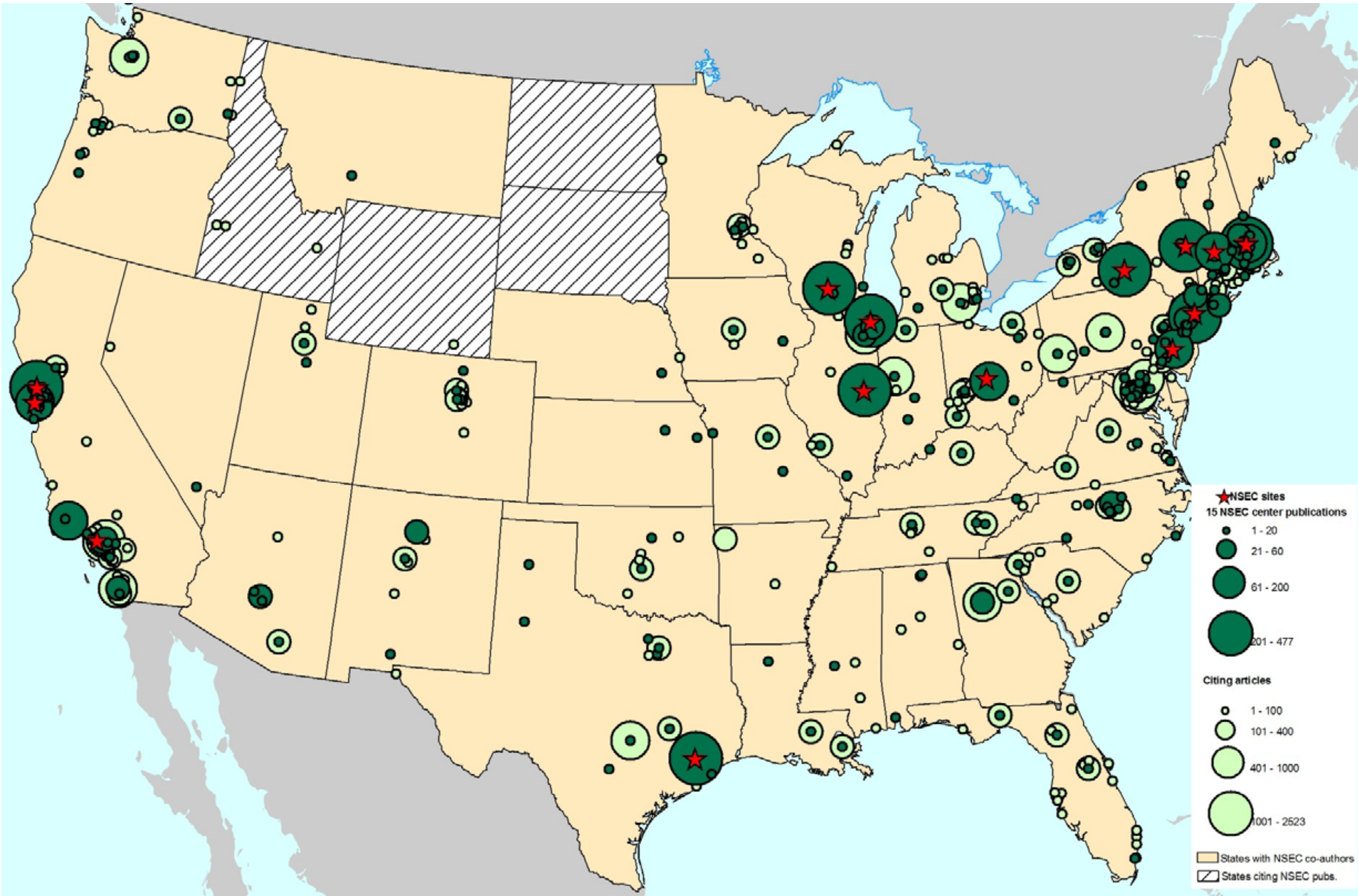


Figure 9. Geographical distribution across the US of center publications and citing articles

a. Publication trends and leverage of support

The positive externalities of program investments in research centers are also perceived in the details of the center activities. Taking the same to illustrative centers as before, we analyzed the sources of support acknowledged in publications by center researchers.

Tables 7 and 8 break down the publication data by attribution of financial support. In order to visualize the patterns for both centers, we represent these data graphically below (Figures 10 and 11). These data indicate the extent to which the activity of the center is able to create synergy -- or leverage with support for other projects -- via joint publication. The graphs indicate for each year how many papers attribute financial support only to the center and which ones were partially supported by the center and by other sources. Given the nature of these data, we cannot tell whether several sources of support are drawn by a single author or if different authors have different sources of support. In either case, the interpretation of the leveraging effect of center support is reasonable.

From these graphs, we can observe that most of the growth in publication output is given by partially supported papers. So the centers, in both cases, are very effective in leveraging NSF center funding to draw support from other sources, reflected here clearly in their productivity. For the center that began activities at an earlier date and seems to have reached a steady state of productivity, the role of partial funding increases and seems to be the main force behind its ability to maintain the steady state.

	2002	***2003***	***2004***	***2005***	***2006***	***2007***	***2008***	**Total**
Publications by year	12	13	27	44	52	50	49	247
• Annual change	N/A	8%	108%	63%	18%	-4%	-2%	N/A
Publications by year (primary funding)	7	8	11	24	30	23	20	123
Publications by year (partial funding)	5	5	16	20	22	27	29	124

Table 7. Publication Trends by Year, Center #1

	2006	*2007*	*2008*	**2009**	**Total**
Publications by year	9	33	59	62	163
• Annual change	N/A	267%	79%	5%	N/A
Publications by year (primary funding)	8	17	11	9	45
Publications by year (partial funding)	1	16	48	53	118

Table 8. Publication Trends by Year, Center #2

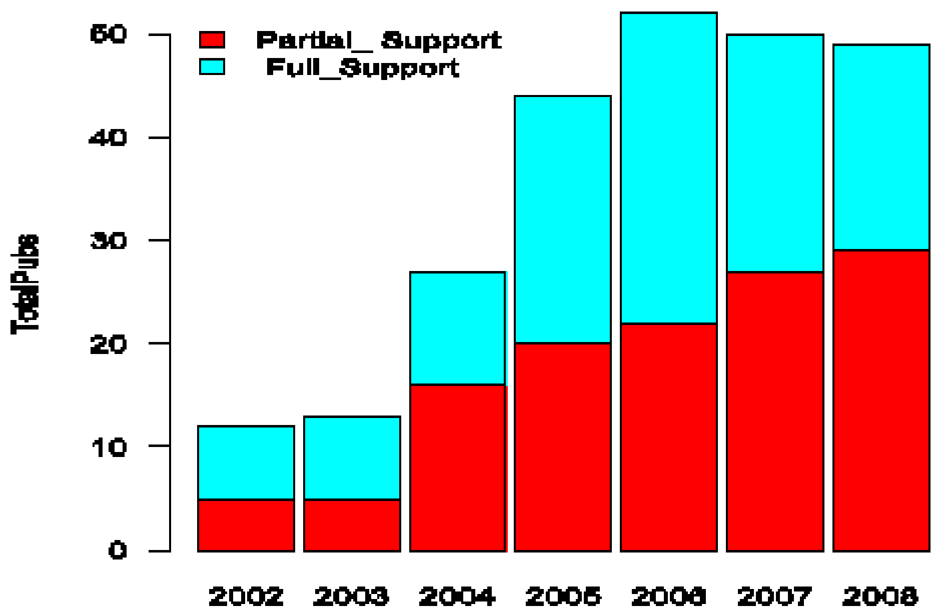


Figure 10. Publication yearly trends w/partial and full funding, Center #1

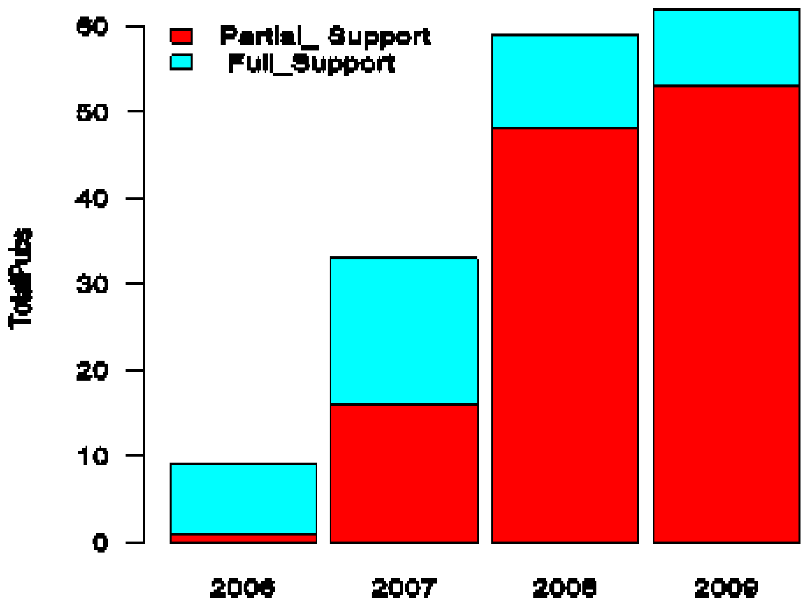


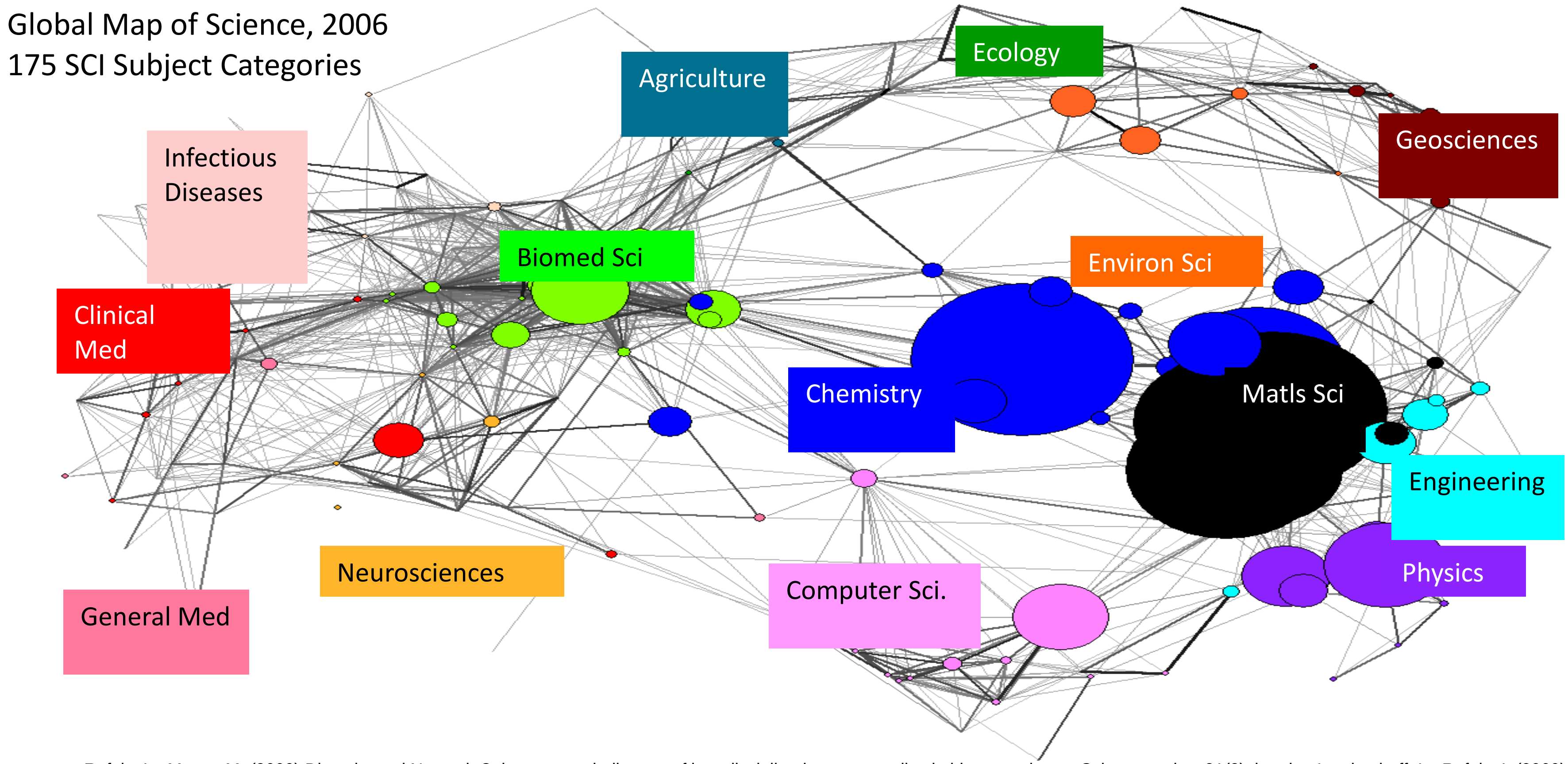
Figure 11. Publication trends by year w/full and partial support, Center #1

In sum, the use of resources seems to be very effectively targeted by leveraging the center program into adjacent program areas, resulting in both a substantive and a resource multiplicative effect. It is important to note that this sort of leveraging is multiplicative, not additive. In other words, this dynamic would not be sustainable without the core resources of the center, so it should not interpreted as a sign of replacement of its sources of support. The triangulation with other sources of information, such as the patterns of collaboration and the spinning off of activities that cannot be considered direct center contributions are further evidence for this interpretation.

d. Interdisciplinarity

Since nanotechnology is an emerging field of science and engineering, it is thought to be at the intersection of several established fields of science. The degree to which this is true is an indirect measure of the novelty contained in this field of research because it grows by differentiating itself from those disciplines.

NSEC research is multidisciplinary with focus areas in materials science, chemistry and biomedical sciences



Map source: Rafols, I., Meyer, M. (2009) Diversity and Network Coherence as indicators of interdisciplinarity: case studies in bionanoscience. Scientometrics, 81(2), in print; Leydesdorff, L., Rafols, I. (2009) A Global Map of Science Based on the ISI Subject Categories. Journal of the American Society for Information Science and Technology, 60(2), 348-362.

Figure 12. Science map of subject categories represented in center publications

A range of disciplines beyond focal areas cite NSEC works

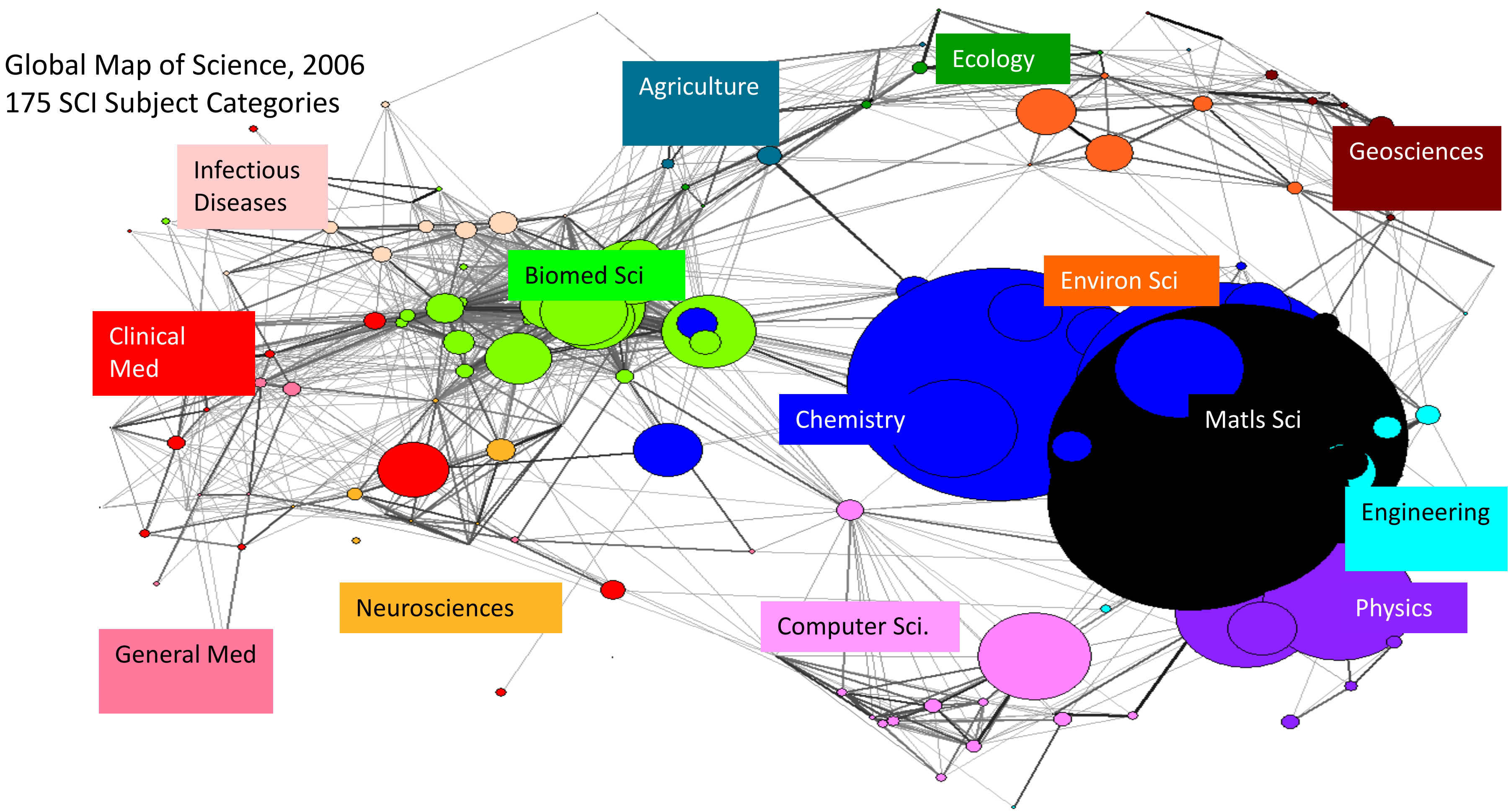


Figure 13. Science map of subject categories represented in publications citing center papers

Figures 12 and 13 contain science-wide representations of the fields of research represented in the center publications and those that cite them. Even though there is a large concentration of subject matter related to chemistry, materials sciences, physics and engineering, research at the centers contains a very diverse combination of disciplinary content. This is both a reflection of nanotechnology itself as a field and of the interdisciplinary nature of center research since centers must draw on faculty and students from these areas to carry out their work.

These maps provide another source of insights into the impact of center research especially if we note that the map of subject categories of citing papers is much more crossdisciplinary than their own publications. This is very noticeable in the case of biotechnology and the life sciences that show a more vigorous citing presence in comparison to the center papers they cite (left side of the map in figure 13).

e. Evolution of research and application topics

i. Keyword analysis of papers and patents

The evolution and influence of the content of research of the NSEC program centers can also be observed by analyzing the keywords of papers and patent applications filed by the centers. This, in turn, addresses two evaluation questions (1) to what extent do patents reflect the research conducted in the NSECs, and (2) are NSECs evolving their research focus over time?

We examined the keywords of the titles of the top five most highly cited research articles authored by each center (149 articles in total[7]) and all patent applications and grants mentioned in the NSECs' annual reports. For the first question, the analysis compares keywords extracted from the titles of these 149 research articles and 638 patents to discern linkages. For the second question, the analysis compares these over two time periods - 2001-to-2005 and 2006-to-2010 – to understand the evolution of

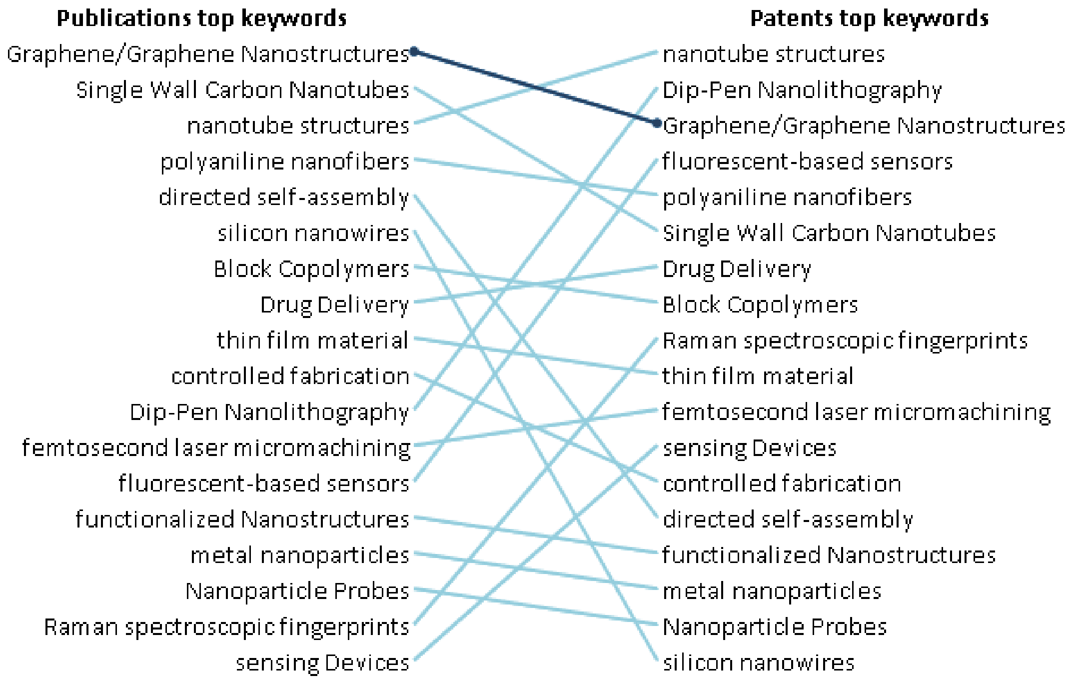
[7] Some centers did not have five articles that attracted citations given their relatively recent startup, so their articles are not included in the first time period.

center research content over time. The extraction of keyword phrases from these article and patent titles was performed using natural language programming algorithms. These keyword phrases were then “cleaned” through grouping similar keyword phrases (e.g. graphene and graphene structures are grouped into graphene/graphene structures.) Regarding the first question, Figure 14 presents a rank comparison for both publication and patent keywords in the 2001-to-2010 time period. This comparison is based on keywords used in both sets of records, which equates to about 7% of the total keywords in all highly cited articles and 12% of the keywords in patent titles.

The results highlight a first set of keywords – e.g., graphene/graphene nanostructures and polyaniline nanofibers – that are prevalent in both highly cited publications and patents. A second set of keywords – e.g., directed self-assembly and silicon nanowires – are more prevalent in highly cited articles than in patents. A third set of keywords – e.g., dip-pen nanolithography, fluorescent-based sensors, and Raman spectroscopic fingerprints – are more prevalent in patents than in articles. It is not surprising that most NSEC research topics do not spillover into patents. Likewise, topics involving nanolithography, Raman spectroscopy, and sensors are more application oriented and thus resonate more strongly on the patent side of the NSECs’ output. However, there is a level of spillover that exists between the research topics of the NSECs’ most influential articles and the types of patents that the NSECs produce.

In the second analysis, we probe how the NSECs have changed their topical emphases over the first and second five years of the duration of the NSEC program. Because of their later grant award dates, some of the NSECs are represented by fewer than five highly cited articles in the first time period.

Figure 14. Rank comparison for top keywords in NLP phrases in publications and patents (2001-2010)



Note: based on keywords mentioned in both publication and patents

Only 20% of publication keywords and 2% of patent keywords in the 2001-2005 time period can be found in the later time period. This finding suggests that the NSECs were set up with sufficient flexibility to allow the centers to switch their research emphases in keeping with new developments in the field.

Table 9 shows top 10 emerging and early-period NLP phrases in both publications and patents. Emerging keywords include those that have been introduced in the second period of analysis (2006-to-2010). Early-period keywords are those that are among the top keywords of the early period (2001-to-2005) but are not used in more recent publications or patents. This comparison between time periods does not use harmonized NLP phrases (it uses cleaned up keywords from each dataset). As the table indicates, prominent publications during the first five years of the NSEC program emphasized nanoparticles (such as fullerenes and nanocrystals) and their attributes (such as band gap fluorescence), as well as microscopy oriented keywords. Articles in the second five years highlight the emergence of polymers along with more application-oriented nanomaterials such as gold nanoparticles and amorphous silicon nanowires. In addition, greater differentiation in the terms is exhibited in the second period -- for example, aberration-corrected microscopy (rather than just microscopy).

Turning to patents, in the first time period there is more emphasis on polymers. We also see the appearance of patents associated with dip-pen nanolithography. As well, generalized nanoparticles are evident in the patents such as magnetic nanoparticles and single-walled carbon nanotubes. Patents in the second five years, in contrast, placed greater emphasis on targeted drug delivery, systems and devices, composites, and graphene. With the exception of graphene in the second time period (and dip-pen nanolithography in the first time period), many of these keywords in the second time period have even more of an application orientation than was seen in patent titles in the first time period.

Top-10 early period NLP phrases (2001-2005) not used in recent publications	Top-10 early period NLP phrases (2001-2005) not used in recent patents
DIRECT ASSEMBLY ACTIVE TIP ADVANCED CARBON-NANOTUBE TRANSISTORS AIR-STABLE ALL-INORGANIC NANOCRYSTAL SOLAR CELLS ALL-OPTICAL CONTROL ARRAY-BASED ELECTRICAL DETECTION ATOMIC FORCE MICROSCOPY BAND GAP FLUORESCENCE C-60 FULLERENE CARRIER INJECTION	SINGLE-WALLED CARBON NANOTUBES DIP-PEN NANOLITHOGRAPHY BIFUNCTIONAL POLYMERS CONDUCTING POLYMERS MAGNETIC NANOPARTICLES FIELD IRRADIATION NANODISPENSING DEVICE COMPOSITE SENSOR MEMBRANES EMBEDDED METAL NANOCRYSTALS FERROFLUIDIC ACTUATED MIXING SYSTEMS

Top-10 emerging NLP phrases in publications (2006-2010)	Top-10 emerging NLP phrases in patents (2006-2010)
ALLOSTERIC DNAZYME CATALYTIC BEACONS AQUEOUS MERCURY IONS ULTRAHIGH SENSITIVITY GOLD NANOPARTICLES ABERRATION-CORRECTED MICROSCOPY AMORPHOUS SILICON NANOWIRE AMPHIPHILIC POLYMERS ARRAY-BASED SENSING ATOMIC FORCE MICROSCOPE TIP BLOCK COPOLYMERS	GRAPHENE ARRAYED CHANNEL NETWORKS MICROFLUIDIC SYSTEMS POLYANILINE NANOFIBERS DRUG DELIVERY GENE DELIVERY MOLECULAR ELECTRONIC DEVICE POLYMER COMPOSITES NMR DEVICES ORIENTED NANOFIBERS

Table 9. Emerging and early-period NLP phrases in publications and patents (2001-2005 and 2006-2010)

The analysis of keywords also gives us another window into the diversity of the research performed by the program centers. Taking the top keywords reported by authors of center papers, we performed a cluster analysis and found that there are multiple interconnected thrusts of research and a few specialized areas that seem more exploratory at the moment. This analysis is represented in figure 14. The graph offers a pictorial representation of the main lines of research of the program centers as reflected in the top keywords and the group overlap.

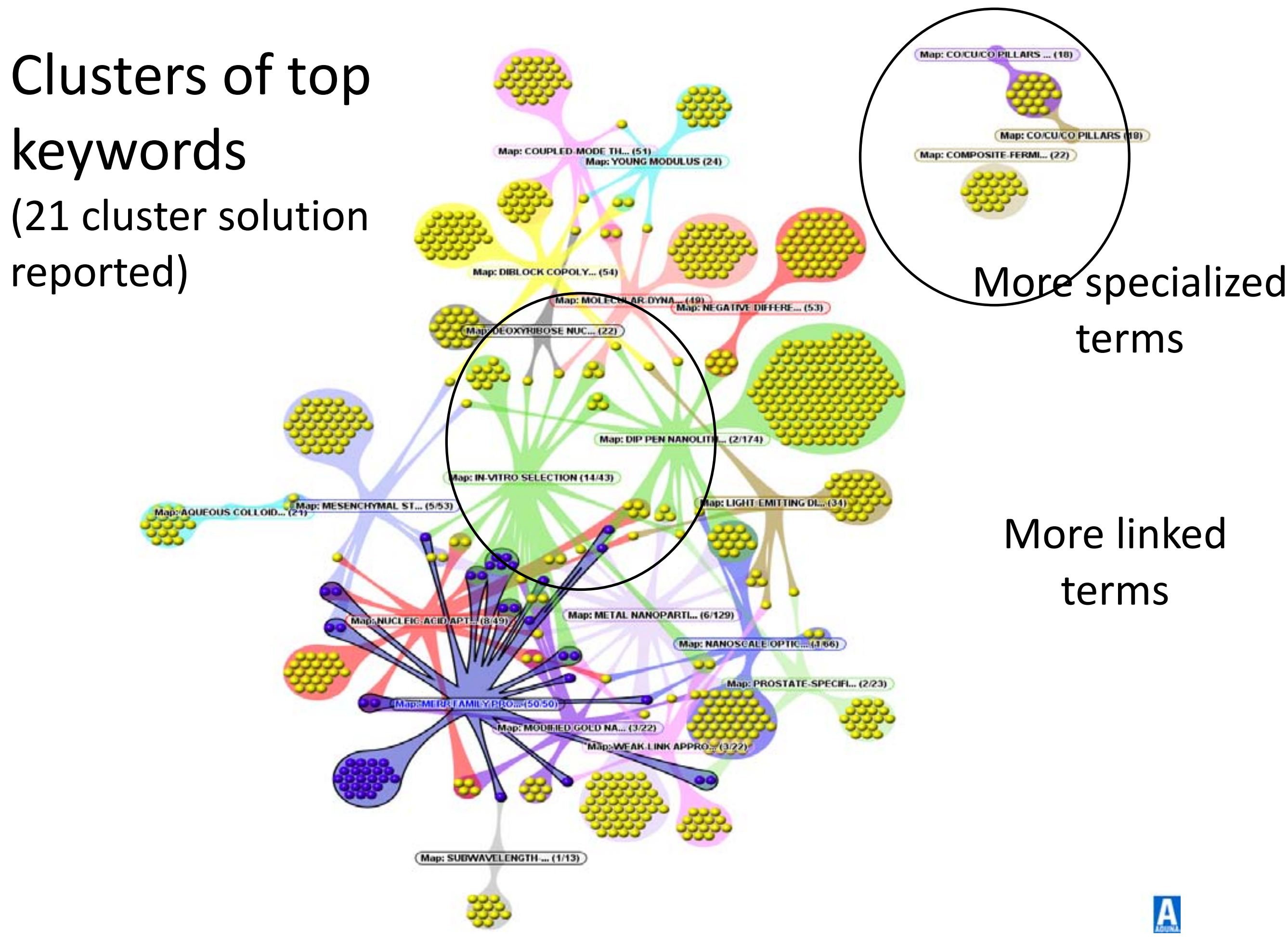


Figure 14. Clusters of top keywords and their overlap

Case in Point: Center for Electronic Transport (Columbia University)

In order to provide a more vivid impression of the main points of research performance we provide a brief description of the activities of one center, the Center for Electronic Transport at Columbia University. It is intended to represent what is more or less typical of the centers in the NSEC program in their own specialty subfields.

This center has made many fundamental contributions to the study of graphene, a monoatomic layer of carbon that has very interesting properties for a variety of applications, especially in electronics. Research in this center was instrumental in establishing the subfield of nanoscale studies of graphene. The center had not proposed to focus originally on this material and worked for some time on the electronic transport characteristics of organic crystals. As this area did not prove to be as fruitful as expected, they were able to move in a new direction, marshalling new resources to find great success with graphene. This is a concrete example of the rapid dynamics of this field in which the centers are able to stay in of the forefront. The center is also a key player in the field of molecular electronics for which it has generated great enthusiasm for cross disciplinary collaboration, both on and off campus. Both of these research areas relied on a visionary strategy of developing talented young faculty. The human resource dimension is integral to the high performance research program using seed grants to allow young researchers to prove themselves. If they do, the center leadership puts resources at their disposal and integrates their ideas into their overall research strategy.

This approach has spilled over to their teaching programs with the installation of highly specialized experimental facilities accessible to students. The overall result has been a very high impact on the interdisciplinary culture of the university as a whole.

Summary of Scientific Outcomes

From the analysis above we conclude that the centers in the NSEC program are producing high quality, high impact scientific results. We have made specific comparisons at the field level to gauge program influence and have determined that the program is producing leading research that has great impact on the field and, in many cases, has been instrumental in opening new fields or transforming existing ones. The NSECs have acquired or developed novel instrumentation and experimental approaches of high impact for several fields.

The program has contributed to the creation of a critical mass of top level talent in virtually all centers. They have been deliberate and strategic in the development of young researchers and, in doing so, have achieved increasing diversity in their research teams.

Research supported by the program is highly interdisciplinary across centers. Even though all centers have made significant efforts to create interdisciplinary environments and teams, the paths and resulting configurations have been interestingly different. There have been two basic mechanisms of interdisciplinarity. Some centers have planned their interdisciplinary activity with periods of mutual training in the basics of their home disciplines to enhance their ability to collaborate. Others have created infrastructure with spaces for free interaction for interdisciplinarity to emerge from chance encounters and adjacent interests. Both have worked in their own way.

The center program and funding support have been critical for the ability to carry out activities of this sort and achieve these results. There is no evidence that these developments would have occurred without not only the funding support but also the guidance and focused interaction that goes with the conditions attached to the grant program.

Linkages with Industry and Commercialization of NSEC Research

The centers have close connections with industry in a variety of ways. Their role in the process of moving research results to commercially viable and impactful applications is diverse and sets up several types of relationships with companies that are involved with nanotechnology.

In this report, we capture a few dimensions of those linkages given the limited nature of this assessment project. The main focus here will be on the connections between the research thrusts in the centers and the sorts of collaborative activity with companies that these lead to. This is a very important dimension because it shows that there is a very permeable boundary between the centers and the companies with which they interact and collaborate. They engage in many close and intense collaborative activities that do not fit easily in a stereotypical classification of transfer or application as a separate, more or less transactional sort of activity with finalized research results. Many companies are closely involved with many of the centers' research activities from their inception. In the next section we develop the evidence for this from the publication record tracking the co-authorships in which one or more co-authors are from industry.

f. Collaboration with industry reflected in co-authored publications

A sense of the importance of the connection of industry to the centers' research can be had from the evolution of the published record of the centers and the presence of industry co-authors. From table 10 we can see that the number of publications with industry co-authors grows with the output of the centers and that, on average, they represent about 10% of all publications across the program.

There were about 360 papers in which centers published with industry co-authors from a total of 146 firms. This indicates that these papers reflect on-going relationships with industry since centers are publishing more than twice with each company on average. It must be noted that this certainly represents a lower bound for the actual collaborations that lead to publications because the rules of reporting outputs for center activities disallow counting publications from projects that are spun off from initial center projects, since they are not strictly part of the center program. Center researchers and PIs informed us that the timing of collaborative activities with centers, especially if they are longer than the center review periods, sometimes leads to continuing collaborations outside of, but adjacent to, the center core activities. So the actual impact of the center-industry relationship is underreported. These data are then a lower baseline for understanding those relationships.

	2001	2002	2003	2004	2005	2006	2007	2008	2009-10*	2001-10*
NSEC centers with publications	3	6	6	13	13	15	15	15	13	15
NSEC publications (all centers)	66	133	221	262	499	515	715	737	361	3,509
NSEC pubslications co-authored with industry	12	13	16	17	35	52	76	65	34	360
▪ *Annual change*		*8%*	*23%*	*6%*	*106%*	*49%*	*46%*	*-14%*	*-48%*	*22%*
▪ *Share industry co-authored / all publications*	18%	10%	7%	6%	7%	10%	11%	9%	9%	10%
Unique co-author firms	11	13	9	16	31	29	50	43	22	146
▪ *Annual change*		*18%*	*-31%*	*78%*	*94%*	*-6%*	*72%*	*-14%*	*-49%*	*20%*

Table 10. Center – industry collaboration reflected in co-authored papers
Notes: * Publication data not reported by all NSEC centers; last column reports average annual change for rows with change data.
Source: ISI-WoS publication data based on NSEC annual reports by center and lists of industry partners provided by NSEC centers.

From the center reports on industry partnerships, we were able to situate the collaborations that lead to publications in the broader collaborative context. There were 421 different companies reported to have some form of partnership with one or more of the program centers. Of these, 360 engaged in collaborations that led to publications in which one or more of their personnel were co-authors. A network graph representing these relationships is presented in figure 15. The nodes are color coded for centers (red) and companies (yellow) and their sizes represent the number of papers for the organization in question. The information in this graph is cumulative over the life of the NSEC program; the centers did not all begin their operation at the same time.

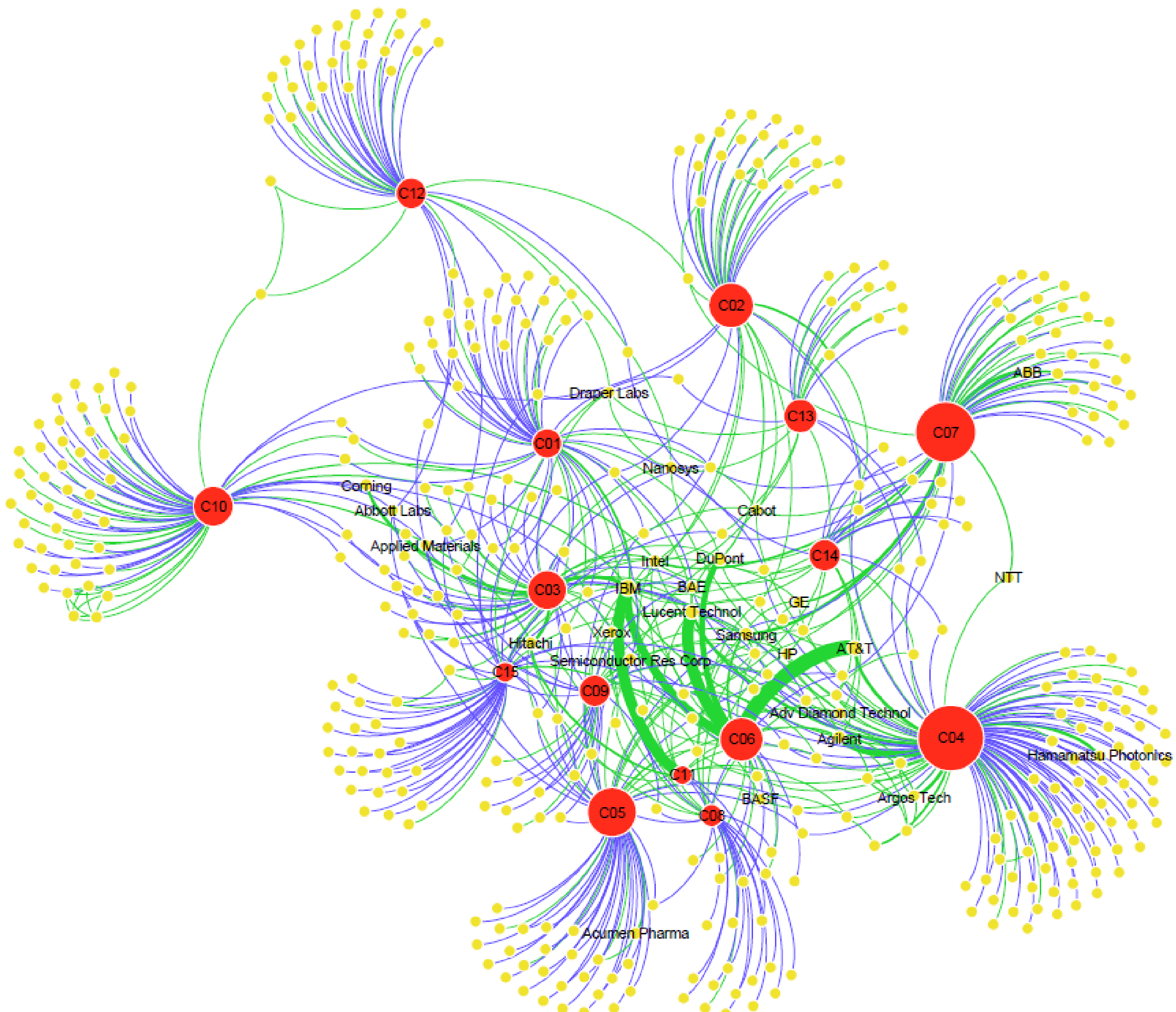


Figure 15. Network representation of collaborations with industry 2001-2010

Notes: Node size represents number of publications in the period 2001-2010. Edge size represents number of co-authorships. Red nodes represent 15 NSECs. Yellow nodes represent industry partners. Green lines represent co-authorships. Blue lines represent other types of collaborations. Labels are shown only for NSEC centers (anonymized) and top-25 industry partners according to number of co-authored publications. The types of collaborations are not specified by centers (only number of industry partners was provided).

Source: Analysis based on list of industry partners provided by NSEC centers as of 2010 and publications in ISI-WoS database for period 2001-2010.

By separating the two overlapping networks of collaborations with co-authored papers from other collaborations with partner companies that do not have co-authored publications, we obtain the representations in figures 16 and 17.

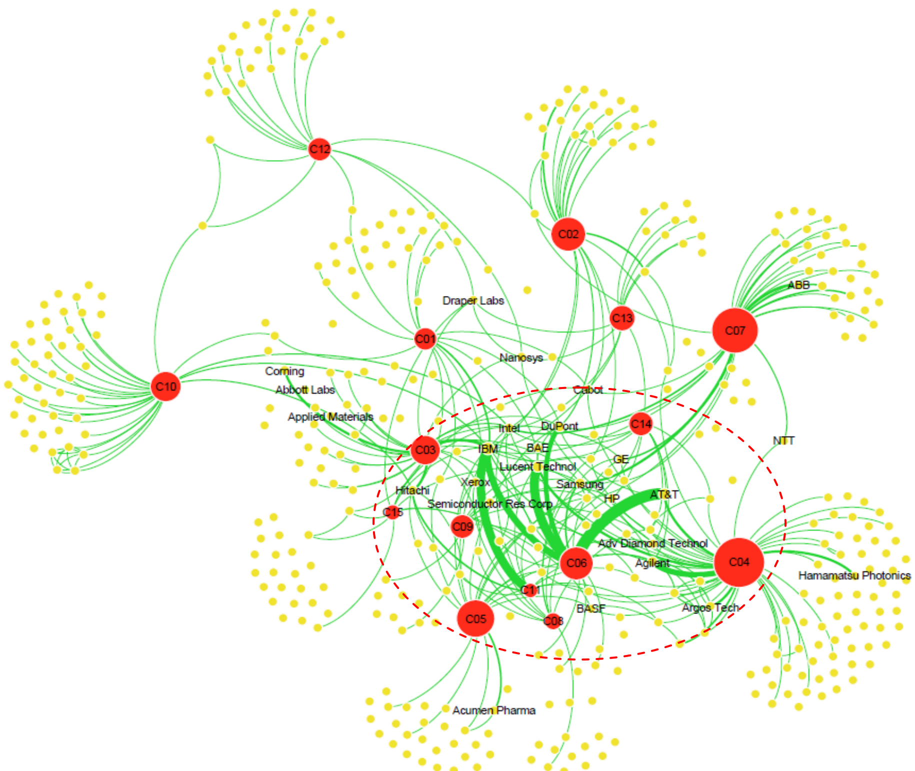


Figure 16. Network of collaborations with co-authored publications (2001-2010)

A distinct pattern can be observed when comparing the two network graphs. The collaborations leading to co-authored publications have a dense cluster of overlapping relationships in which a core group of companies collaborates with many centers. In other words, the deeper, shared research collaborations that take place with centers are a program level phenomenon, not an individual center one. Even though the centers are reviewed and selected individually, some companies have relationships with these centers as if the centers were pre-designed as a network. The center program and these companies have developed a collaborative network that has grown in time and suggests an R&D system in its own right.

The network of collaborations with no co-authored publications is sparser in the center but has many links to individual companies that cluster with little overlap with each individual center. These clusters are mostly spinoff companies that are initiated by entrepreneurs residing in incubators associated with the university and attracting venture capital for future development.

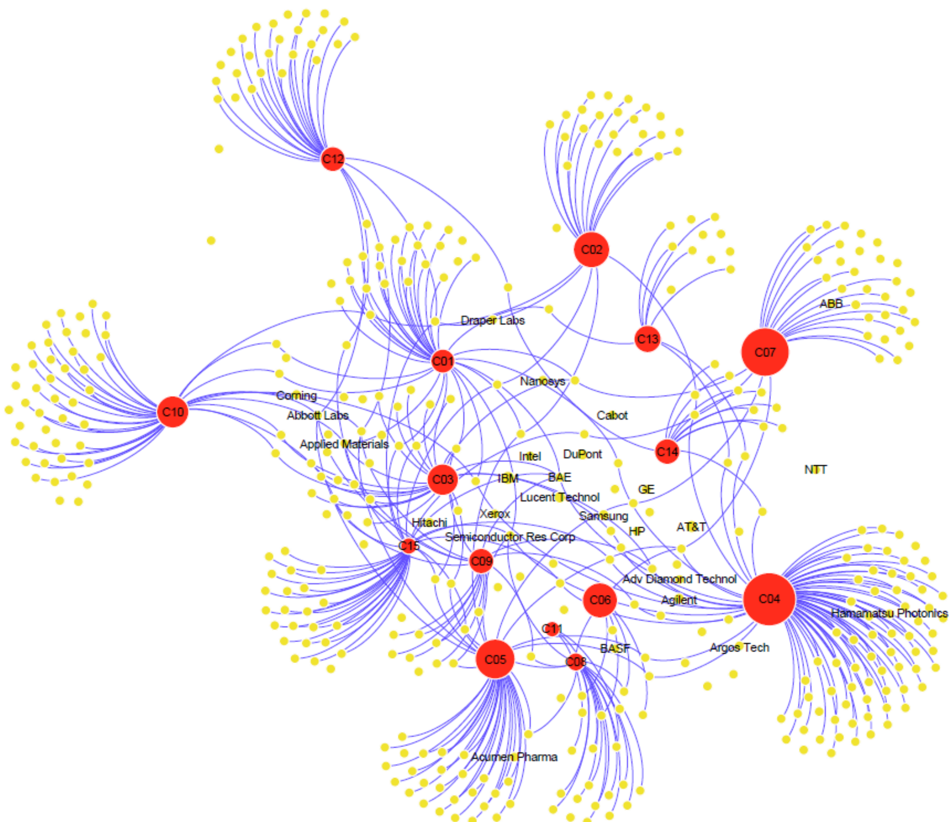


Figure 17. Collaborations with industry not resulting in co-authored publications (2001-2010)

Taking a closer look at the core of collaborations with industry with co-authored publications, we observed that there is a set of relatively large companies that collaborate with several centers at once (Figure 18). Clearly, there is a diversified strategy of relationships with industry that is pursued by all centers in the program. At the same time, it seems clear that the cluster of companies that conducts nanotechnology R&D in collaboration with the centers has come to rely on it as a networked resource for research.

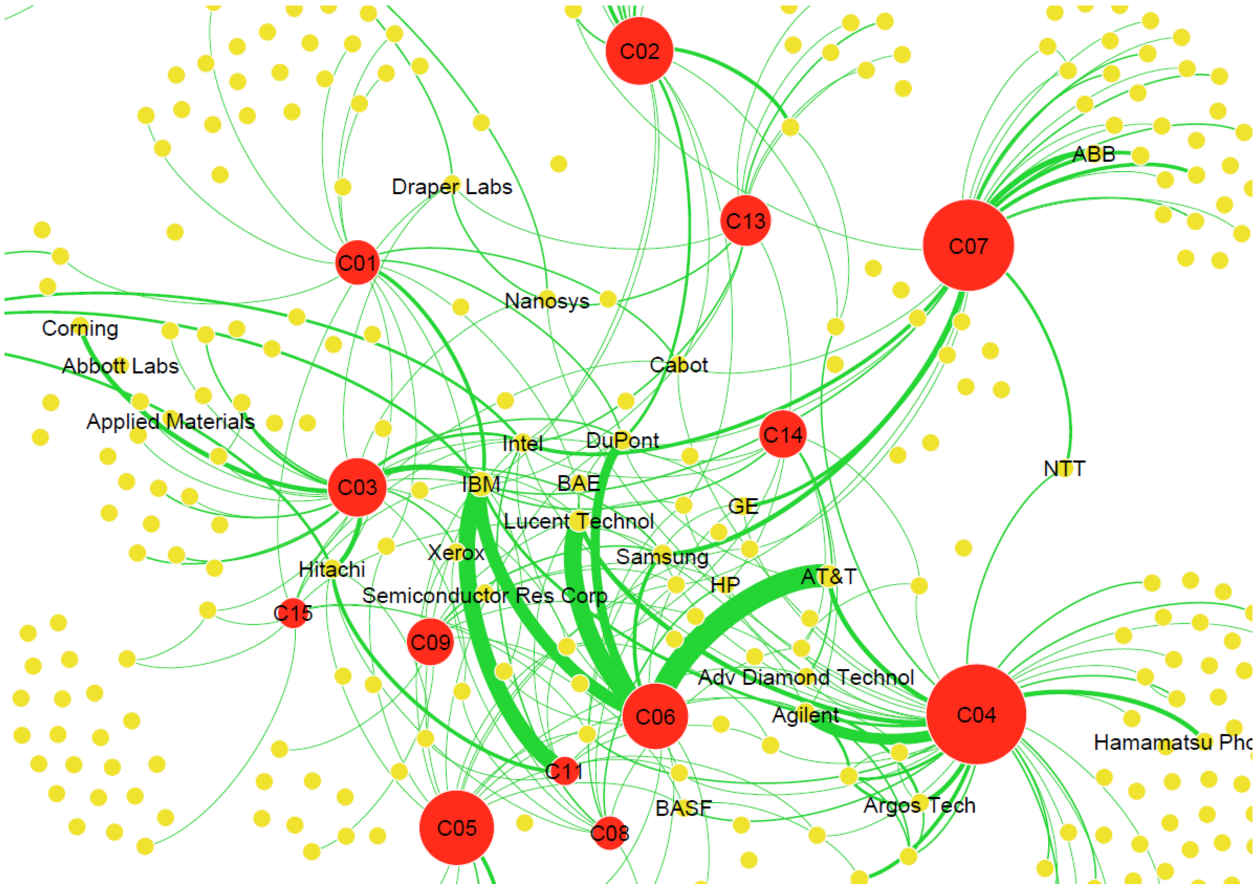


Figure 18. Expanded view of the core of the network of collaborations with co-authored publications

The bar chart in figure 19 shows the nature of this network system in terms of the number of companies and the number of links to centers. There are 25 companies who have published with co-authors from more than one center and 17 have done so with 4 centers or more. Five companies have co-authored papers with at least 6 different centers. From these collaborations we can see the remarkable significance of this center program for the nanotechnology innovation system in the United States.

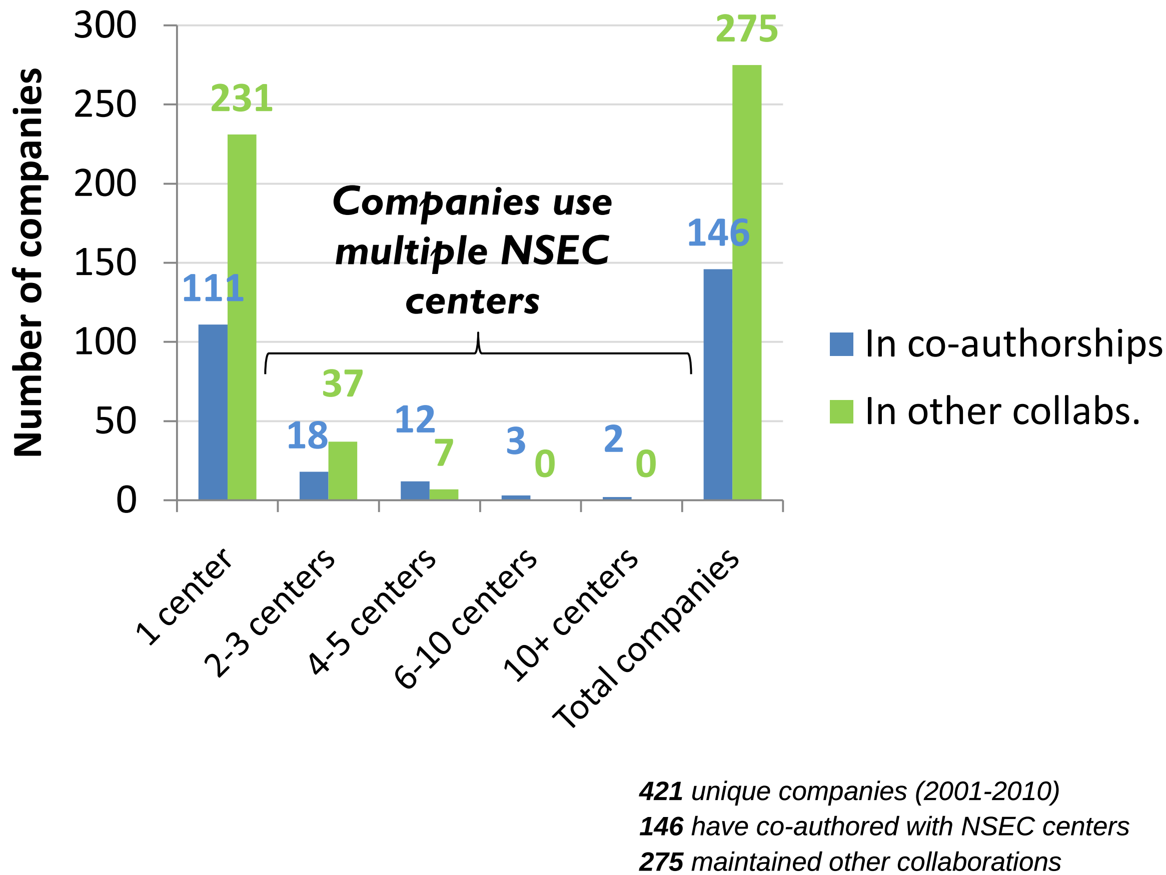


Figure 19. Bar chart representation of collaborations with industry

In order to illustrate the program level analysis presented in this section, we include a specific case of one center, which represents a typical pattern of these centers, and another case to represent the types of commercial outcomes from center research.

Case in Point #1: The Center for Affordable Nanoengineering of Polymeric Biomedical Devices (Ohio State University)

The Center for Affordable Nanoengineering of Polymeric Biomedical Devices at Ohio State University provides a good example of many of the points made above. The center has engaged in a dual strategy of commercialization with an entrepreneurship component and collaborations with established companies as the second component.

The center has generated several spinoff companies on the basis of the intellectual property resulting from center R&D. It combines the scientific and technical content of these ventures with an entrepreneurship program in cooperation with the university's business school. Teams of students with an industry mentor each compete for awards and receive opportunities to create companies based on center research.

On the side of partnerships with established companies, the center has leveraged the polymer industry cluster in the state of Ohio by designing its nano-science and technology agenda to facilitate the engagement with companies in the region. This nano-science work is pursued for its potential to revitalize the traditional rubber and polymer industries in the state. They also engage in beta-testing of prototypes and materials for partner companies using the specialized facilities that belong to the center. The engagement with the established companies has led to projects that transcend the focus of the center because they require longer development times than the center funding and reporting cycles allow. The center reports a very large volume of interactions with industry along all dimensions.

Case in Point #2: Nanospectra Biosciences (http://www.nanospectra.com)

Professor Jennifer West, an early career scientist at Rice, did not have any single principal investigator grants before the NSEC Center for Biological and Environmental Nanotechnology (CBEN) was established. CBEN provided a significant amount of funding, which was eventually followed by a research grant from the National Institutes of Health. What is now one of the most highly cited papers among the NSECs came out of this work: Nanoshell-mediated near-infrared thermal therapy of tumors under magnetic resonance guidance, *Proceedings Of The National Academy Of Sciences Of The United States Of America,* Hirsch, LR; Stafford, RJ; Bankson, JA; Sershen, SR; Rivera, B; Price, RE; Hazle, JD; Halas, NJ; West, JL, 2003 --728 citations.

This paper involved multidisciplinary work between biomedical engineering, electrical and computing engineering, chemistry, and a multidisciplinary cancer center, among others. The paper involved the creation of gold nanoshells. This work gave rise to

Nanospectra Biosciences founded in 2002. The company attracted $6 million in financing from angel investors, private investment funds, and the Texas State Emerging Technology Fund, which contributed more than $1 million for clinical trials. The company also attracted $1.5 million in series A funding. It was an early nanomedicine company which set a path for commercialization with the US Food and Drug Administration. The company is now in Phase 2 clinical trials for head and neck cancer.[8]

Other examples of significant venture investment in NSEC spinoff firms include NanoTerra (soft lithography, nanofabrication) – $20 million in venture investment from the Science of Nanoscale Systems and their Device Applications (Harvard); and Ohmx Corporation (bioelectronic monitoring device) –$5.1 million in venture investment from the Integrated Nanopatterning and Detection Technologies center (Northwestern) . The NSECs appear to serve as a signal to the market for commercial investment of select spinoffs.

Summary Findings on Commercialization

Centers have fluid and diverse relations with companies. All centers have dual strategies focusing on entrepreneurship, on the one hand, and on collaboration and partnerships with established firms, on the other hand.

The evolution of relationships with companies reflects significant organizational learning. As collaborative activities take place and early results or obstacles emerge, the path forward for commercialization may reflect different timing requirements. Some worthy collaborative activities require longer time than the funding and reporting cycles of the centers allows and they are pursued outside of the program purview and, therefore, not perceived as contributions of the center or the NSEC program. The progress of collaborations may also present choices that were not foreseen. In some cases companies and centers may view them from different priority standpoints leading

[8] Sources: Interviews with center personnel at CBEN, August 17, 2010 and Nanospectra Biosciences web site: http://www.nanospectra.com

to challenging issues in the management of the partnership. The centers have incorporated many lessons from these experiences into a variety of collaborative arrangements and approaches.

A large proportion of the transfer of technology to industry is carried out through the movement of graduates out to the workforce. Industry partners, more often than not, hire former students of the centers that the companies got to know through the collaborative activities with the centers.

Some centers have developed an enormous volume of commercial activity, both in the number of instances of collaboration with industry and also with the financial magnitude of some of their projects or transactions. They have also developed the ability to impact multiple companies through standards development, regional industry clusters, work with consortia, and access to test beds, among other mechanisms. There is evidence that a set of large companies, all leaders in high technology, have come to rely on the centers in the NSEC program as an R&D system, working simultaneously with several centers on overlapping interests.

Finally, all centers have research that leads to patenting activity. The 2001-2010 period is short to see the full development of this process since it takes several years for research to be completed until it is worthy of a patent application and then it takes several more years for the patent to be granted. This was covered in the previous section in connection with the keyword analysis.

Workforce and public perception

The centers in the NSEC program are heavily involved in education at several levels. Since they are located on university campuses and are an integral part of the universities that receive the grants to set them up, it is naturally expected that graduate and undergraduate programs would be direct targets for their educational roles, and they are. However, it important to point out that the centers' contributions to the development of a highly trained workforce in nanotechnology includes objectives that transcend the university classroom in two directions. On the one hand, as we already mentioned in connection with the research agenda setting, centers are carrying out their world class R&D mission by developing the most promising young researchers they can recruit. A generation of very special researchers is grown from the activities of the centers, which is an educational/labor force component in itself.

On the other hand, centers are charged with the mission of helping to improve pre-college STEM education in ways that they see fit. There are numerous rather creative efforts carried out by centers in this regard which we report on below. This educational role is well integrated into the core research and commercialization activities of the centers. We consider some of the specifics of this role in two parts: one devoted to a variety of educational innovations at all levels that can be observed at the centers; a second relates to the education of the public on the content and meaning of nanotechnology, providing context for the more focused educational efforts that centers carry out.

a. Educational innovations

In the most direct area of influence of the center, namely, graduate and undergraduate students on their own campus, all centers have developed courses and programs in nanotechnology with a variety of emphases and modalities. These range from courses that are integrated into existing engineering and science undergraduate and graduate programs, minors and certificates, to full blown undergraduate and graduate programs in nanotechnology. There is no particular scale for assessment of the significance of these initiatives. They are mainly designed to fit within their existing educational environment. What the centers offer students in these programs, besides the up-to-date content informed by the centers' research, is a variety of research experiences in their unique facilities and with top researchers in the field. The results include 1,233 graduates (at the master's, doctoral, and postdoctoral levels) as of August 2010. More than one-third of these graduates are employed in private industry, including 44% of master's degree graduates.

All centers are required to contribute broadly to educational goals, including pre-college STEM education. This has been the case for NSF-funded centers in previous programs. The evolution of the approaches used by centers has been significant. In the past, the lack of experience of university researchers with pre-college education and the needs of teachers generally led to outreach programs that were run by non-research personnel specially hired for these efforts. While those produced generally valuable results, they were generally perceived as peripheral activities to the core research mission of the centers.

The NSEC program, however, has fully integrated these efforts into the core mission of the centers and we observed that the principal researchers were directly involved in their design and implementation. Centers in the program have created many different approaches to contribute to pre- and extra-college STEM education showing great creativity and taking advantage of lessons learned from previous center experiences. The details of these approaches and efforts would take too much space to describe in detail and most information about them can be obtained from individual center websites and materials. It suffices to point out that one major area of significant results has been the development of science teacher professional development programs in a variety of formats. These include workshops and research experiences designed on the basis of researched needs and objectives for teachers seeking to maximize pre-college classroom impact. In some instances these also include innovative multimedia productions and modules that can be used in various educational settings.

b. Public diffusion innovations

Outreach to the general public is not an educational mission in the same vein as new graduate and under-graduate programs or pre-college science teacher professional development. However, the centers do engage in significant outreach efforts that show the priority this has for the NSEC program. Remarkably, across the program, center researchers and principals are actively involved in the design and implementation of these efforts as well. Center leaders involve their students in the events that are often very sophisticated productions. Some of these efforts that many centers engage in include center open houses or “Nano-Days” in which members of the centers use multimedia productions or presentations and displays, lab visits and demonstrations, to help lay persons understand the nature of the research conducted in the center. Some centers have partnered with museums in their area to create exhibits that remain on display for the public for extended periods of time. The designs of these exhibits and displays involves the participation of researchers and students and are taken on as truly interdisciplinary efforts in their own right. A number of documentary films has been produced by several centers and made available to broadcasters or to the public through the centers’ websites.

We illustrate these general points with two cases from different centers to give a clearer impression of how these efforts are carried out.

Case in Point #1: NSEC for Nanoscale Systems (Cornell University)

In this case, the center principal investigators designed a strategy for education that was integral to the core activities of the center. They did not separate this aspect of the center’s mission for third party contracting, as had been the case in many centers in the past. The addressed the pre-college science teacher professional development, as it related to their nanotechnology focus, as one more dimension of the set of interdisciplinary problems that needed resolution. Cornell engaged in an empirical investigation of the science teachers population in order to ground the design of their program on the basis of such results. The resulting design was carefully crafted to address and assessed the identified set of needs of the teachers.

The initiative included a summer professional development program that granted university credit towardprofessional development requirements recognized by the school system. From the program itself and the experiences of cohorts of teachers that came through it, they designed a set of laboratory modules for classroom use that was then packaged for remote availability in a lending library run by the university.

The program has impacted about half of the total population of science teachers in the state and the overall program design has been exported for implementation in other states. This constitutes knowledge transfer on a par with the concerns for commercialization of nanotechnology results, for example.

Case in Point #2: NSEC for Integrated Nanopatterning and Detection Technologies (Northwestern University)

Two particularly innovative programs were designed and implemented in this center. First, a focused research program for the involvement of undergraduates aimed to insure that students who participated had a true research experience in its entirety rather than just support work for the research of others. Undergraduate students are encouraged to pursue their ideas in collaboration with researchers and graduate students who offer advice and mentoring. This experience takes them all the way to include the process of publication of their results. As a result, a unique scientific journal in the field of nanotechnology that showcases undergraduate research was created. After some time, undergraduates from across the world submit manuscripts for publication in the journal. The journal is supervised by graduate students and faculty to insure the quality and originality of the submissions. But the actual work is entirely carried out by undergraduates. The journal has established itself as a reputable scientific journal and continues to showcase undergraduate research.

This center entered a partnership with the Chicago Museum of Science and Industry. Principal investigators of the center collaborated with the museum curators to design and set up a world class nanoscience and nanotechnology exhibit on display for the general public at a premier museum. This display was carried out with a high level organizational commitment on the part of the center and many of its members reflecting its high priority as part of the center’s mission.

Support for Responsible Development of Nanotechnology: Societal Implications

The fourth goal of the NNI that the centers funded by the NSEC program must contribute to is to support the responsible development of nanotechnology. The societal implications of nanotechnology that may have to be considered as choices present themselves for the development of nanotechnology are difficult to ascertain. The NSEC program has funded two centers with the specific task of doing research on this question and providing perspectives to prepare for those choices in the best way possible. Those two centers were not included in this study because those of us conducting this assessment have ties to them and would be presented with conflicts of interest. However, all centers must contribute to the realization of this goal in ways that emerge from their focused areas.

For some centers, the societal implications seem direct and easier to articulate. They are related to the substantive content of their research in ways that do not require new problem formulations. Among these are health and environmental aspects of nanotechnology that centers such as the Center for Biological and Environmental Nanotechnology (CBEN) at Rice University or the Center for Hierarchical Manufacturing (CHM) at the University of Massachusetts have clear societal dimensions to their research and examples of activities and projects in this area follow.

Members of CBEN participate in standards committees in the United States (ANSI Technical Advisory Group) and globally ((ASTM International Committee E56) contributing to the creation of the nomenclature for nanotechnology objects and phenomena. These are the first components and tools used in the creation of rules for future industrial and consumer standards to insure safety and consideration of other public concerns. CBEN researchers also founded the International Council on Nanotechnology (ICON) “to develop and communicate information regarding potential environmental and health risks of nanotechnology, thereby fostering risk reduction while maximizing societal benefit."[9] The center has also conducted studies of water purification especially as it relates to the effects of nanoparticles in water resources in developing countries. It has also supported historical studies of nanoscience and nanotechnology to acquire perspective on the implications of the field for governance. This work will contribute to ability of agencies such as the EPA and FDA in their regulatory functions vis a vis emerging nanotechnologies.

CHM has also pursued several connections of its research program to broader societal issues, such as a survey of nanotechnology industry leaders; a case study of technology transfer institutions at the University of Massachusetts; new measurement approaches to studying environmental, health and safety effects of nanoparticles in complex samples; a study of online resolution of intellectual property disputes involving nanotechnology; and public perceptions of nanotechnology from media and public culture portrayal.

These are not unique examples across centers but represent the cases in which the core center research focus has direct societal problems so they are naturally part of their research agenda. In other cases, the consequences for responsible development of nanotechnology are less obvious and require an interdisciplinary effort in their own right. It should be noted that the first wave of NSECs was not initially required to address societal implications upon receipt of the first five-year award, though addressing societal implications is a current program requirement.

Summary findings on Societal Implications

The centers across the program show a diverse, but not very integrated, effort in this dimension. Many of these efforts arise naturally out of the research agenda of the centers and represent high quality contributions, especially in the health and environment areas. Some consider the potential risk and disbenefit consequences

[9] http://icon.rice.edu/ (Rice, CBEN)

arising from some center topical foci. There is also evidence of support for investigation of ethical dimensions of research in biomedical topical foci. In some cases, efforts directed at increasing the diversity of center participation in terms of gender and ethnic background are interpreted as contributions to this goal.

We conclude that there is an important and difficult challenge in this area of which the NSEC program is aware, but may be a more difficult interdisciplinary frontier than has previously been realized. The problems in this dimension have a lesser degree of articulation as truly interdisciplinary problems than some of the core nanotechnology topics themselves or even the educational dimension that has seen remarkable integration across the program.

Conclusions

The analysis of the evidence shows that the centers contribute to the goals of the NNI program in some distinct ways. In this report we have chosen not to enumerate all the activities and outputs and financial figures that describe a large volume of activity. This information is directly available from public sources and center reports. Rather, we offer a focused interpretation of the nature of the outcomes and impacts in connection with the four goals of the NNI in order to communicate the particular shape of its contributions in the context of the broader field of nanotechnology in the United States and around the world.

Goal 1: Advance world-class nanotechnology R&D.

Aside from the usual indications of productivity and tracking of output, which all seem to be at high rates, the contributions to true world-class nanotechnology R&D are evident from the close tracking by global research organizations of NSEC publications. The analysis of organizations with which citing authors are affiliated shows that European and Asian research organizations stay abreast of the centers' publication. After the impact on the continuation of its own work, reflected by citations within the home institution, it was global research organizations that cited the centers' work more highly.

Secondly, the centers seem to consistently increase their impact with time as indicated by the growing presence of their publications in the highest impact journals over the life of the centers. Papers cannot be fairly compared for quality on a one-to-one basis using the journal impact factors because they may reflect different aspects of a body of work and their relevance for others will not be the same. Many projects will have both great breakthroughs and incremental advances to take the implications of that breakthrough to fruition in many concrete secondary results. The body of publications will reflect this distribution of efforts. Both centers that we profiled in more depth seemed to reflect the growth in middle impact journals, where many concrete results would be published, and a smaller absolute number, but growing in time, set of high impact papers in journals such as *Nature* and *Science.* Actually the mix in these in the body of output may be more important than the individual items themselves.

Third, an analysis of the citations to early cohorts of papers from the centers shows that they are among the most highly cited papers in the field as a body of literature. The entire set of publications by the centers is at the top of the distribution of citations for the field with many highly ranked papers, and median citations doubling and tripling the median for the field.

Fourth, the comparison of overlay maps for center publications, and citations by others of those publications, shows a very significant spillover effect of center research into adjacent fields that are not the target of their own publications. This speaks to breadth of impact of NSEC research and to its interdisciplinarity in a way that is not ordinarily observed. The work itself has definite interdisciplinary features, as seen by the measures of specialization and integration. These show that there is significant integration of knowledge in different fields and that the set of subfields of centers' output is also diverse. However, the way others pick up the centers' output in fields outside of their publication targets is also a significant indication of the implications for cross-disciplinarity of the NSECs' work.

Goal 2: Foster the transfer of new technologies into products for commercial and public benefit

The analysis of publication co-authorship also speaks to the contribution of NSECs to this goal. Centers also become more and more involved in a very deep intellectual way with R&D organizations in the private and government sectors, as reflected by the growing number of papers co-authored by NSEC researchers and researchers from these entities. The lists of collaborating organizations and of the affiliations of those who cited NSEC papers attest to this. The network analyses illustrate the phenomenon further. With respect to companies, in recent times the short time horizons for their expectations of return on investment highlight the fact that they get involved in research when they have a clear sense of its connection to commercial applications.

Second, the network graphs are a very good indication of the richness of links of the NSECs with industrial partners. Centers collaborate with an average of 20 companies each and many top companies have multiple relations with several centers at the same time. This evidence, combined with the publication record, suggests a variegated set of links with industry. It seems that a core of top high technology companies has come to rely on the program centers as an R&D resource, as indicated by the multiple collaborations with several centers simultaneously.

Goal 3: Develop and sustain educational resources, a skilled workforce, and supporting infrastructure to advance nanotechnology

The centers are heavily involved in educational activities that contribute to this goal at several levels. First, virtually all centers have developed courses and programs for graduate and undergraduate students that aim to establish the field into the future with generations of new professionals and researchers in nanotechnology in both research institutions and private industry.

Second, they accelerate the career paths of promising young researchers converting many of them into remarkable “stars” in the field by targeting support and mentoring. The cases are too many to ascribe this phenomenon to a coincidence. In this sense, the research strategies of the centers are fully integrated with a human resources strategy that develops the talent they need to pursue the ambitious scientific and technical goals.

Third, centers have developed creative approaches to pre-college science teacher professional development and public diffusion of nanotechnology. These have been approached as truly interdisciplinary problems in their own right involving the principals of the centers in their design and implementation.

Goal 4: Support responsible development of nanotechnology

The main effort of the NSEC program toward this goal is being carried out by two specialized centers on societal dimensions that were not part of this project due to the potential for conflicts of interest (since the researchers on this project have connections with those centers). So our contribution to the assessment of the realization of this goal is only partial. However, all the centers have activities that are aimed at this component of the NNI.

First, we observed that some of the specialized research activities of the centers are naturally related to societal dimensions that have an effect on the responsible development of nanotechnology. For example, those centers that work on health and environmental aspects of nanotechnology address problems of a societal nature that are configured within their field of research. For other centers, this connection is more indirect and the formulation of the problems is not within their current purview. In those cases, the efforts on societal dimensions seemed less well integrated with the research focus of the centers.

Center Evolutionary Tracks

A number of program level conclusions that are not directly related to NNI goals emerge from the analysis of these data that may be useful for other program management tasks. For example, the evolution of support seems to follow a regular pattern of diversification by leveraging without substitution of core funding. Second, the expectations for the process of start up and steady state are informed by our findings. There is a one to two year period of focusing and then a level of activity that can be expected to be reached by years four or five. These findings should prove to be useful in future program design and management.

Some Program Challenges

There are some challenges that may be worth considering in the design of future versions of the NSEC program. Even though the program has been intent on including the diffusion of information to the general public, it is still true that some scientific contributions are difficult to explain to the lay public and that the general support of the public is important for the long term viability of the enterprise. Therefore, continued efforts on this with more integrated approaches with the general research thrust of the centers' research are necessary. Some centers were very successful with highly innovative approaches to this issue.

The partnerships with industry produced many remarkable outcomes but also showed some difficulties that deserve attention for future program designs. As partnerships with companies develop over time, many contingencies emerge that cannot be foreseen at the inception of their collaboration. The current arrangements did not always allow for the pursuit of worthy collaborations and some that did continue could not be ascribed to center efforts. Some of the frustration associated with these contingencies can be eased with relatively small revisions of the rules of engagement. Others may require broader rethinking of the expectations of academic-industry interactions.

Some of the benefits of having centers on campus could be expanded to the rest of the academic community that hosts the center. For example, the mechanisms for the development of faculty and graduate students should be scaled up to reach the rest of the university. Similar strategies might help the development of younger faculty in other departments that are not directly affiliated with the centers. Some of the potential tensions between centers and other campus entities could be eased considerably if some thought is given to this.

Finally, the societal impacts studies are not well integrated and seem distant as an interdisciplinary challenge. This is probably not due to a defect in the current program design or to underperformance of the centers. As the history of center development reveals in the case of approaches to education, the configuration of the problems in this area as a new frontier of interdisciplinary problems that are not disjoint with the main scientific and technical foci of the center might yield promising results.

The Case for Centers

A lingering question in the academic community and its counterparts in the funding agencies has to do with the advantages or disadvantages of having center programs such as the NSEC program or more individual project programs with a single PI or a small team of collaborators. Our assessment of the NSEC program leads us to conclude that the center approach for this field has produced some unique results. The evidence for this conclusion concerns continuation of the work on nanotechnology for which this program has laid such a significant foundation. It does not speak to center funding mechanisms in other scientific fields.

The NSEC program has provided a unique incentive to go deeply across disciplinary boundaries. It has significantly reduced cross-disciplinary transaction costs, which has paved the way for new fields and subfields that would not have developed as rapidly otherwise.

The program has also provided a unique research experience for graduate students with a rich and diverse research infrastructure that enables more risk taking, and exposure to a greater number of high quality scientific contacts and an equally unique set of industry contacts.

The NSEC program has also become an accelerator of promising young researcher development in which the centers were specialized recruiting tools of top talent. They also had the appropriate context for diverse mentoring opportunities for rapid career development that are much more difficult to expect in traditional departments.

The program also gave centers the ability to develop unique infrastructure and facilities. It allowed center principal investigators to leverage center resources for building shared new facilities with campus, industry, and state and local government support. In this context, the program also facilitated the design of new unique instruments and experimental arrangements that could not have been done in more decentralized environments. It is important to understand that leveraging is a multiplicative effect that may evolve into requiring less core support to maintain its leverage by adjusting a ratio. However, what is acquired by leverage ceases to exist if the lever provided by the core funding is eliminated because its effect is not additive. In other words, if the NSEC program were to be eliminated, the fact must accepted that much of the infrastructure development will be lost.

The pre- and extra- university education efforts are also dependent on the center program and are difficult to institutionalize without it. Their sustainability should be a program concern looking into the future.