

Connecting NSF Funding to Patent Innovation in Nanotechnology (2001 – 2004)

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Abstract

Nanotechnology research has experienced growth rapid in knowledge and innovations; it also attracted significant public funding in recent years. Several countries have recognized nanotechnology as a critical research domain that promises to revolutionize a wide range of fields of applications. In this paper, we present an analysis of the funding for nanoscale science and engineering (NSE) at the National Science Foundation (NSF) and its implications on technological innovation (number of patents) in this field from 2001 to 2004. Using a combination of basic bibliometric analysis and content visualization tools, we identify growth trends, research topic distribution, and the evolution in NSF funding and commercial patenting activities recorded at the United States Patent Office (USPTO). The patent citations are used to compare the impact of the NSF-funded research on nanotechnology development with research supported by other sources in the United States and abroad. The analysis shows that the NSF-funded researchers and patents authored by them have significantly higher impact based on patent citation measures in the four-year period than other comparison groups. The NSF-authored patent impact is growing faster with the lifetime of a patent, indicating the long-term importance of fundamental research.

Keywords: *patent citations, patent analysis, information visualization, self-organizing maps, nanoscale science and engineering, nanotechnology, research and development (R&D), technological innovation, government funding.*

1. Introduction

Nanoscale science and engineering (NSE) is an interdisciplinary field with wide implications in knowledge generation, industry and biomedical applications, and sustainable environment. Its application areas include advanced materials, detecting and treating disease, monitoring and protecting the environment, producing and storing energy, and building complex structures for electronic circuits. Nanotechnology is expected to have a significant impact on numerous economic sectors, and is a national R&D priority in about 60 countries. In 2000, the United States announced the *National Nanotechnology Initiative* (NNI, www.nano.gov) based on a long-term vision (Roco et al., 2000). Since then, more than 60 countries have adopted national projects or programs partially stimulated by the NNI (Roco, 2005). Increased attention is being given to

stimulating nanotechnology innovation leading to economical benefits. The NNI investment has exceeded \$1 billion in fiscal year 2005, and NSF has the largest program with a budget over \$340 million in the same year. Gaining an understanding of the effect of public funding on the NSE research and innovation through the number of patents may contribute in shaping recommendations for future funding policies.

We previously proposed an approach for assessing and mapping the development of the NSE field through analyzing patent documents (Huang et al., 2003). This was based on the current patent analysis literature (Garfield, 1955; Karki, 1997; Oppenheim, 2000). Scientific evaluation of the impact of public funding on research output and on the overall development of a scientific and engineering field is a difficult task and only sparse literature exists on this topic. The difficulty of associating research output with the general development of a field was documented by Adams and Griliches (Adams and Griliches, 1998). Most previous studies focused on the impact of public funding on research output based on scientific publications (Adams and Griliches, 1998; Arora and Gambardella, 1998; Narin, 1998; Payne and Siow, 2003). In our previous research, we used patent documents and their citations in order to provide a more direct account of the impact of public funding from NSF on technological innovations between 1991 and 2002 (Huang et al., 2005).

In this paper, we focus on nanotechnology research and development (R&D) in the interval 2001 to 2004 using the patents in the USPTO database and the funded awards from the NSF database. These are the first four years of the National Nanotechnology Initiative (NNI). After defining the NSF award and USPTO patent datasets used for the study, we assess the growth trends of the published patents and awards in the NSE field that reflect the research productivity and funding activity. The technology topic areas in NSE patents and awards are presented in topic maps that reveal topic distributions and the evolution of funded research and patents in the field. Statistical analyses are used to compare the patents and inventors funded by NSF awards with those supported by other resources based on the patent citation measures.

2. NSF Award Data and USPTO Patent Data

Patent Data

The USPTO patent database provides full-text access to USPTO filed patents since 1976. From 2001 to 2004, USPTO issued 737,176 patents. We used an NSE keyword list to collect NSE-related patents by searching title, abstract, claim, and description of the patent documents (“full-text” search) (Huang et al., 2004; Huang et al., 2003). The resulting set of NSE patents contains both the patents having nanotechnology products (identified in title, abstract and the claims) and the patents using nanotechnology tools (typically described in the text). Our dataset contains 32,180 NSE patents (“full-text” search) issued during 2001-2004, invented by 53,597 authors from 9,470 assignees in 97 countries. These patents are associated with 386 (out of a total of 462) first-level United States Patent Classification categories. Using the same NSE keyword list, we also collected NSE-related patents by searching title, abstract, and claim of the patent

documents ('title-claims' search) (Huang et al., 2004). The result set contains 6,253 NSE patents, invented by 11,449 authors from 2,325 assignees in 53 countries. These patents are associated with 298 (out of a total of 462) first-level United States Patent Classification categories. The "full-text" search results provide better coverage of the NSE patents, and the "title-claims" search results provide better accuracy. In this research, we focused on the "full-text" search. We also reported the "title-claim" search results as a comparison.

Table 1. Top assignee countries: Number of patents (2001-2004) identified by keyword "full-text" search

Rank	Assignee Country	Number of Patents 2001-2004	Percentage of all NSE patents (32180)
1	United States	21120	65.63%
2	Japan	3899	12.12%
3	Germany	1133	3.52%
4	France	883	2.74%
5	Canada	545	1.69%
6	Republic of Korea	394	1.22%
7	United Kingdom	375	1.17%
8	China (Taiwan)	354	1.10%
9	Netherlands	291	0.90%
10	Australia	288	0.89%
11	Switzerland	240	0.75%
12	Israel	194	0.60%
13	Sweden	160	0.50%
14	Italy	137	0.43%
15	Belgium	111	0.34%
16	Denmark	84	0.26%
17	Singapore	75	0.23%
18	Finland	73	0.23%
19	India	55	0.17%
20	Ireland	42	0.13%

Table 1 lists the top 20 assignee countries according to the numbers of NSE-related patents ("full-text" search) issued between 2001 and 2004. In these years, the United States produced the majority of the NSE patents, followed by Japan, Germany, France, and Canada.

Table 2. Top assignee countries: Number of patents (2001-2004) identified by keyword "title-claims" search

Rank	Assignee Country	Number of Patents 2001-2004	Percentage of all NSE patents (6253)
1	United States	4147	66.32%
2	Japan	501	8.01%
3	Federal Republic of Germany	246	3.93%
4	France	192	3.07%
5	Republic of Korea	162	2.59%
6	China (Taiwan)	126	2.02%
7	Canada	91	1.46%

8	Netherlands	65	1.04%
9	United Kingdom	62	0.99%
10	Switzerland	43	0.69%
11	Israel	42	0.67%
12	Australia	35	0.56%
13	Belgium	33	0.53%
14	Italy	30	0.48%
15	Singapore	25	0.40%
16	Sweden	24	0.38%
17	India	19	0.30%
18	Ireland	16	0.26%
19	China	10	0.16%
20	Denmark	9	0.14%

Table 2 shows the top 20 assignee countries according to the number of NSE-related patents by “title-claims” search between 2001 and 2004. In this interval, the United States produced the majority of the NSE patents, followed by Japan, Germany, France, and Korea.

Table 3. Top assignee institutions: Number of patents by “full-text” search (2001-2004)

Rank	Assignee Name	Number of Patents
1	International Business Machines Corporation	730
2	Micron Technology, Inc.	620
3	Advanced Micro Devices, Inc.	519
4	The Regents of the University of California	461
5	Minnesota Mining and Manufacturing Company	396
6	Xerox Corporation	356
7	Intel Corporation	268
8	General Electric Company	239
9	NEC Corporation	234
10	Motorola, Inc.	227
11	Eastman Kodak Company	219
12	Canon Kabushiki Kaisha	181
13	Corning Incorporated	165
14	Applied Materials, Inc.	162
15	Hewlett-Packard Development Company, L.P.	162
16	Hitachi, Ltd.	154
17	Massachusetts Institute of Technology	144
18	Silverbrook Research PTY LTD	143
19	Kabushiki Kaisha Toshiba	142
20	Fuji Photo Film Co., Ltd.	141

Table 3 shows the top 20 assignee institutions according to the numbers of NSE-related patents published between 2001 and 2004. In these years, the top five assignees are International Business Machines Corporation (IBM), Micron Technology Inc, Advanced Micro Devices Inc, the Regents of the University of California, and Minnesota Mining and Manufacturing Company (3M).

We used the first-level United States Patent Classification categories (available at: <http://www.uspto.gov/go/classification/selectnumwithtitle.htm>.) as representations of the patents' technology fields. In this ontology, some categories have identical names; however, the detailed specifications of such categories are different. We used the category name and the U.S. Patent Classification ID number to label each technology field. Table 4 presents the top 20 technology fields according to the numbers of the NSE-related patents issued between 2001 and 2004. Technology fields "435 Chemistry: molecular biology and microbiology," "438 Semiconductor device manufacturing: process," "257 Active solid-state devices," "514 Drug, bio-affecting and body treating compositions," and "424 Drug, bio-affecting and body treating compositions" are at the top of the list.

Table 4. Top U.S. patent technology fields: Number of patents by "full-text" search (2001-2004)

Rank	Technology Field	Number of Patents
1	435: Chemistry: molecular biology and microbiology	4191
2	438: Semiconductor device manufacturing: process	3249
3	257: Active solid-state devices (e.g., transistors, solid-state diodes)	3030
4	514: Drug, bio-affecting and body treating compositions	2923
5	424: Drug, bio-affecting and body treating compositions	2549
6	536: Organic compounds -- part of the class 532-570 series	2251
7	428: Stock material or miscellaneous articles	2236
8	530: Chemistry: natural resins or derivatives; peptides or proteins; lignins or reaction products thereof	1776
9	427: Coating processes	1542
10	250: Radiant energy	1468
11	359: Optics: systems (including communication) and elements	1299
12	430: Radiation imagery chemistry: process, composition, or product thereof	1284
13	436: Chemistry: analytical and immunological testing	1151
14	356: Optics: measuring and testing	1004
15	385: Optical waveguides	889
16	422: Chemical apparatus and process disinfecting, deodorizing, preserving, or sterilizing	849
17	524: Synthetic resins or natural rubbers -- part of the class 520 series	793
18	204: Chemistry: electrical and wave energy	706
19	252: Compositions	655
20	313: Electric lamp and discharge devices	616

Award Data

The NSF funds science and engineering through research and education awards (grants, contracts, fellowships, and cooperative agreements). NSF accounts for about 20 percent of federal support to academic institutions for basic research (NSF, <http://www.nsf.gov/home/grants.htm>). In 2005, more than 5% of the NSF budget was dedicated to support NSE research.

The NSE-related NSF award dataset was provided by the NSF. The dataset was created by matching the award title, program, and abstract ("title-abstract" search) in the NSF's

award database using an NSE keyword list. Although this keyword list is slightly different from the one used for patent collection (Table 5), domain experts believe that they have similar coverage. To ensure the accuracy and coverage of our NSE award dataset, the large awards (over \$0.5 million) were checked manually to ensure their relevance to the NSE field. We also added the awards that came from the Nanoscale Science and Engineering solicitations that were missed by the search.

Table 5. Keyword lists used for patent and award collection

Patent Collection Keywords	Award Collection Keywords
atomic force microscope	afm
atomic force microscopic	
atomic force microscopy	
atomic-force-microscope	
atomic-force-microscopy	
atomistic simulation	
biomotor	
molecular device	
molecular electronics	
molecular modeling	molec mod*, molec* mod*
molecular motor	molec motor
molecular sensor	
molecular simulation	
nano*	nano*, nems
quantum computing	
quantum dot*	quantum dot
quantum effect*	
scanning tunneling microscope	stm
scanning tunneling microscopic	
scanning tunneling microscopy	
scanning-tunneling-microscope	
scanning-tunneling-microscopy	
self assembled	
self assembling	selfassembl
self assembly	self assembl*
selfassembl*	
self-assembled	
self-assembling	
self-assembly	

We identified 3,891 NSE-related awards out of the total 43,855 awards issued by the NSF between 2001 and 2004. These awards have 5,957 investigators and were made by 44 NSF divisions and 712 NSF programs. For both the patent and award collection, the majority of the documents were obtained by searching the keyword ‘nano*’ (91% of the patent collection and 88% of the award collection).

Tables 6 and 7 present the top 20 NSF divisions and programs according to the numbers of NSE-related awards issued during 2001-2004. The Division of Materials Research (DMR) was dominant with more than a quarter of the total number of NSE awards, followed by the Division of Design, Manufacture and Industrial Innovation (DMI);

Division of Chemistry (CHE); Division of Chemical and Transportation Systems (CTS); and the Division of Electrical and Communication Systems (ECS). The top 5 NSF Programs funding NSE research were: Major Research Instrumentation (Program 1189); Electronics, Photonics, and Device Technologies (Program 1517); Small Business Phase I (Program 5371), Condensed Matter Physics (Program 1710); and Polymers (Program 1773).

Table 6. Top NSF divisions funding the NSE research: Number of awards (2001-2004)

Rank	Division	Number of Awards
1	DMR Division of Materials Research	997
2	DMI DIV OF Design, Manufac & Industrial Innov	505
3	CHE Division of Chemistry	466
4	CTS Division of Chemical & Transport Systems	408
5	ECS Division of Electrical & Communications Systems	381
6	CMS Division of Civil & Mechanical Systems	217
7	CCF Division of Computing and Communications Foundations	150
8	OISE/INT Office of International Science and Engineering	143
9	DMS Division of Mathematical Sciences	127
10	BES Division of Bioengineering & Environmental Systems	111
11	EEC Division of Engineering Education & Centers	104
12	CCR DIV OF Computer-Communications Research	93
13	PHY Division of Physics	77
14	MCB Division of Molecular & Cellular Biosciences	59
15	EAR Division of Earth Sciences	57
16	DBI Division of Biological Infrastructure	47
17	DUE Division of Undergraduate Education	46
18	EIA Division of Experimental & Integ Activit	30
19	EPS Office of Exper Prog to Stim Comp Rsch	20
20	DGE Division of Graduate Education	17

Table 7. Top NSF programs funding the NSE research: Number of awards (2001-2004)

Rank	Program	Number of Awards
1	1189 MAJOR RESEARCH INSTRUMENTATION	235
2	1517 ELECT, PHOTONICS, & DEVICE TEC	218
3	5371 SMALL BUSINESS PHASE I	202
4	1710 CONDENSED MATTER PHYSICS	164
5	1773 POLYMERS	104
6	4710 DES AUTO FOR MICRO & NANO SYS	100
7	1750 INSTRUMENT FOR MATERIALS RSRCH	97
8	1414 INTERFAC TRANS,& THERMODYN PRO	81
9	1676 NANOSCALE: EXPLORATORY RSRCH	80
10	1775 ELECTRONIC MATERIALS	78
11	1972 ELECTROCHEMISTRY & SURFACE CHE	75
12	1762 SOLID-STATE CHEMISTRY	62
13	1771 METALS	60
14	1788 NANOMANUFACTURING	54
15	1765 MATERIALS THEORY	53
16	1630 MECHANICS & STRUCTURE OF MATER	51
17	1415 PARTICULATE & MULTIPHASE PROCSS	50

18	1765	CONDENSED MATTER & MAT THEORY	49
19	5373	SMALL BUSINESS PHASE II	49
20	1674	NANOSCALE: INTRDISCPL RESRCH T	39

Comparing the major NSF divisions that support NSE research and the technology fields of patents filed in the NSE area, we observe that the dominant NSF divisions are related to material science, chemistry, and device design. This finding is consistent with the related technology areas reflected in the patent data. However, the dominant fields related to biology and pharmaceutical research in NSE patents were not reflected in major NSF divisions. This difference may reflect the NSF’s mission and respective decision to differentiate its funding scope in the NSE field from other federal funding agencies such as the National Institutes of Health. Another explanation would be the higher level of competitiveness and confidentiality in several areas such as pharmaceutical industry.

Linking the NSF Award and USPTO Patent Data

The key linkage we rely on to analyze the impact of NSF funding on NSE research and development is the set of inventors who received funding from NSF awards and filed NSE patents (Huang et al., 2004). Specifically, we have identified the NSE patent inventors who were also the principal investigators of NSE-related NSF awards in past years. We refer to them as “PI-inventors” in the rest of the paper. To identify a more complete assessment of the PI-inventors, we used the NSE patent data from 1976-2004 and the NSF award data from 1991-2004 for inventor-investigator mapping. Details regarding the complete NSE patent dataset can be found in our previous papers (Huang et al., 2003). We identified 705 PI-inventors using name and institution matching in the award and patent datasets. Among these PI-inventors, there are 524 PI-inventors associated with 839 NSE patents and 747 NSF awards in the time period from 2001 to 2004. In this research, we deem these patents to be the research results of the NSF-funded research conducted by the PI-inventors.

3. Trend Analysis

In recent years, the NSE field experienced a rapid growth. Tables 8 and 9 show the NSE-related USPTO patents and NSF awards publication trends between 1991 and 2004. In the table, patents refer to the NSE patents published in the USPTO each year. New awards refer to the awards started in the respective year. Active awards refer to all awards with funding in the respective year, no matter the starting year.

Table 8. Trend analysis: the numbers and percentage of USPTO patents (1991-2004)

Year	Number of NSE Patents for "full-text"	Number of NSE Patents for "title-claims"	Number of All Patents	NSE Patents Percentage for "full-text"	NSE Patents Percentage for "title-claims"
	Search	Search		Search	Search
1991	1,864	290	107,259	1.74%	0.27%
1992	2,088	371	108,156	1.93%	0.34%
1993	2,303	346	110,540	2.08%	0.31%
1994	2,032	343	114,564	1.77%	0.30%
1995	2,734	452	114,764	2.38%	0.39%

1996	2,719	471	122,953	2.21%	0.38%
1997	3,906	598	125,884	3.10%	0.48%
1998	4,989	752	166,801	2.99%	0.45%
1999	5,559	860	170,265	3.26%	0.51%
2000	5,884	952	176,350	3.34%	0.54%
2001	7,015	1,219	184,172	3.81%	0.66%
2002	7,733	1,382	179,764	4.30%	0.77%
2003	8,630	1,670	187,147	4.61%	0.89%
2004	8,802	1,982	181,443	4.85%	1.09%

Table 9. Trend analysis: the numbers and percentage of NSF awards (1991-2004)

Year	Number of NSE New Awards	Number of All New Awards	New NSE Awards Percentage	Number of NSE Active Awards	Number of All Active Awards	Active NSE Awards Percentage
1991	153	10,645	1.44%	222	27002	0.82%
1992	176	10,832	1.62%	383	32985	1.16%
1993	235	9,748	2.41%	542	35409	1.53%
1994	273	10,429	2.62%	736	37083	1.98%
1995	309	9,843	3.14%	941	37822	2.49%
1996	325	9,575	3.39%	1,083	37775	2.87%
1997	365	10,256	3.56%	1,226	37219	3.29%
1998	453	9,919	4.57%	1,390	37266	3.73%
1999	525	9,645	5.44%	1,586	37342	4.25%
2000	716	10,478	6.83%	1,905	38377	4.96%
2001	823	10,485	7.85%	2,367	39365	6.01%
2002	910	10,923	8.33%	2,911	40693	7.15%
2003	1,255	11,592	10.83%	3,596	42924	8.38%
2004	1,172	10,893	10.76%	3,694	44209	8.36%

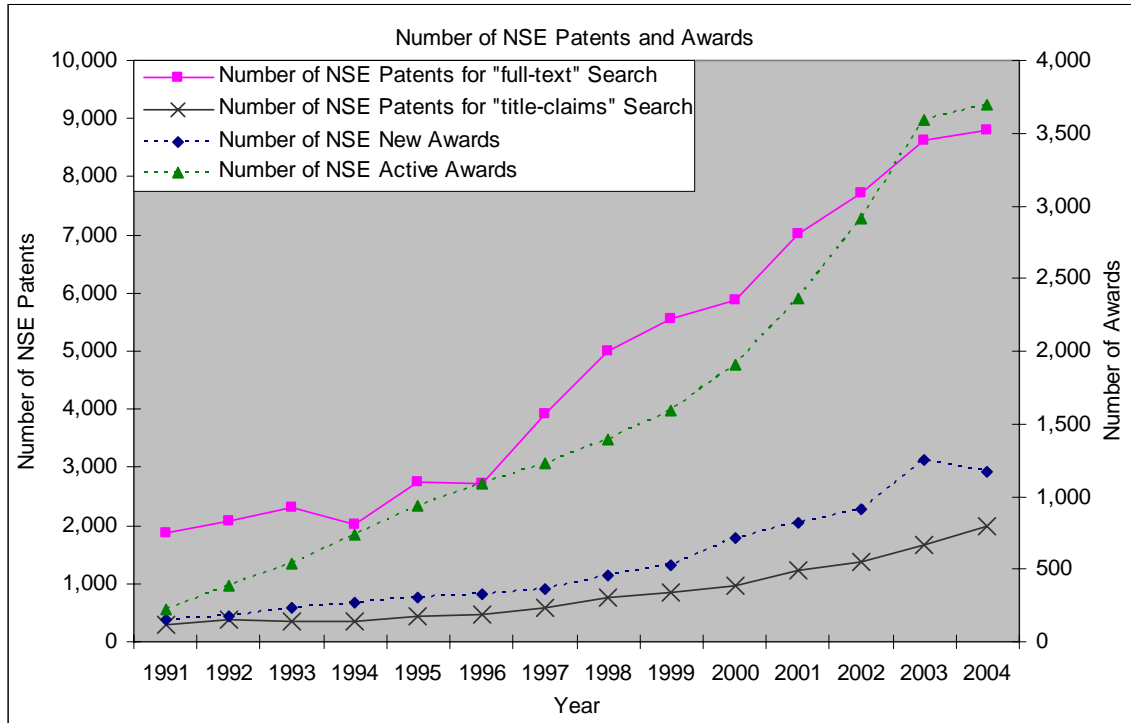


Figure 1. Trend analysis: number of USPTO patents and NSF awards (1991-2004)

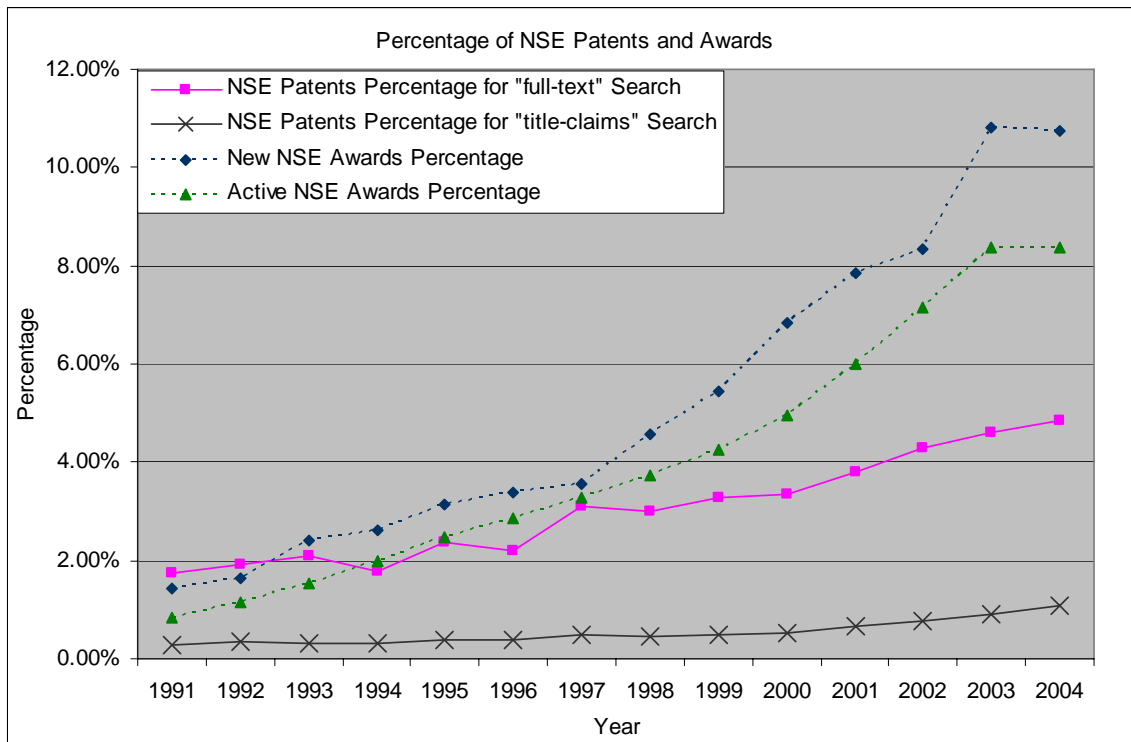


Figure 2. Trend analysis: percentage of USTPO patents and NSF awards (1991-2004)

Figure 1 illustrates the number of patents for “full-text” search and “title-claims” search, as well as the number of new awards and active awards between 1991 and 2004 reported in Tables 8 and 9. The patents and awards published in the interval 2001-2004 represent a significant percentage of all NSE patents published between 1991 and 2004. An almost identical number of NSE patents (by both search methods) were published between 2001 and 2004 and between 1991 and 2000. More NSE-related awards were awarded between 2001 and 2004 than between 1991 and 2000.

Figure 2 shows the proportion of NSE patents/awards as compared to the total number of patents/awards, respectively. One observes that the NSE patents/awards percentage is increasing (see Table 7 and Figure 2). After 2003, more than ten percent of new NSF awards were in the NSE field fully or partially.

4. Topic Map Analyses

We applied advanced text analysis and visualization techniques (topical maps) to both the NSE awards and patents in order to identify the major NSE research topics.

The topic map interface contains two components, a folder tree on the left-hand side and a hierarchical content map on the right-hand side. The nodes in the folder tree and colored regions in the content map are technology topics extracted from award/patent documents using a Natural Language Processing tool, the Arizona Noun Phraser, which can identify the key noun phrases based primarily on the linguistic patterns of free texts. The technology topics in the content map are organized by the multi-level self-organization map algorithm (Chen et al., 1996; Ong et al., 2005) developed by the Arizona Artificial Intelligence Lab. This algorithm produces hierarchical groupings of award/patent documents, in which conceptually closer technology topics were positioned closer geographically. Conceptual closeness was derived from the co-occurrence patterns of key phrases in document titles and abstracts. The folder tree corresponds to the colored region layers generated by the algorithm. Numbers of patent documents that were assigned to the different levels of topics are presented after the topic labels. The sizes of the topic regions also generally correspond to the number of documents assigned to the topics (Lin et al., 2000). This content mapping tool was applied for NSE patent analysis in our previous studies (Huang et al., 2004; Huang et al., 2003).

The NSE patent/award content maps for the time intervals of 2001-2002 and 2003-2004 (Figures 5 and 6) visualize the changes of topic areas from the previous time period. The growth rate of a topic area was computed as the ratio between the number of documents in the current time period and that of the previous time period. A baseline growth rate was computed as the ratio between the total number of documents in the current time period (2001-2002 and 2003-2004, respectively) and that of the previous time period. A topic region with similar growth rate to the base growth rate was assigned a green color that is consistent with the region color in the 2001-2002 content maps. The higher (lower) the growth rate of a topic region is, the warmer (colder) the color assigned. The red indicate the new research topics.

Topic Map Analysis for 2001-2002

Figures 3 and 4 present NSE award and patent content maps from 2001 to 2002 respectively. Figure 3 shows that in 2001-2002, NSF-funded NSE awards cover 26 topics, which are concentrated in “microscope”-related topics, “quantum”-related topics and “molecular”-related topics. Figure 4 shows that NSE patents cover broader technology topics (37 topics in total) including “optical fibers,” “thin films,” “nucleic acids,” “electromagnetic radiation,” “semiconductor substrates,” “semiconductor devices,” and “pharmaceutical compositions.” As the topic labels are noun phrases extracted using the Arizona Noun Phraser, their capitalization varies. However, phrases with capitalization as well as morphological and inflectional variations were treated as the same phrase for the patent/award topic area representation used by the self-organizing map algorithm.

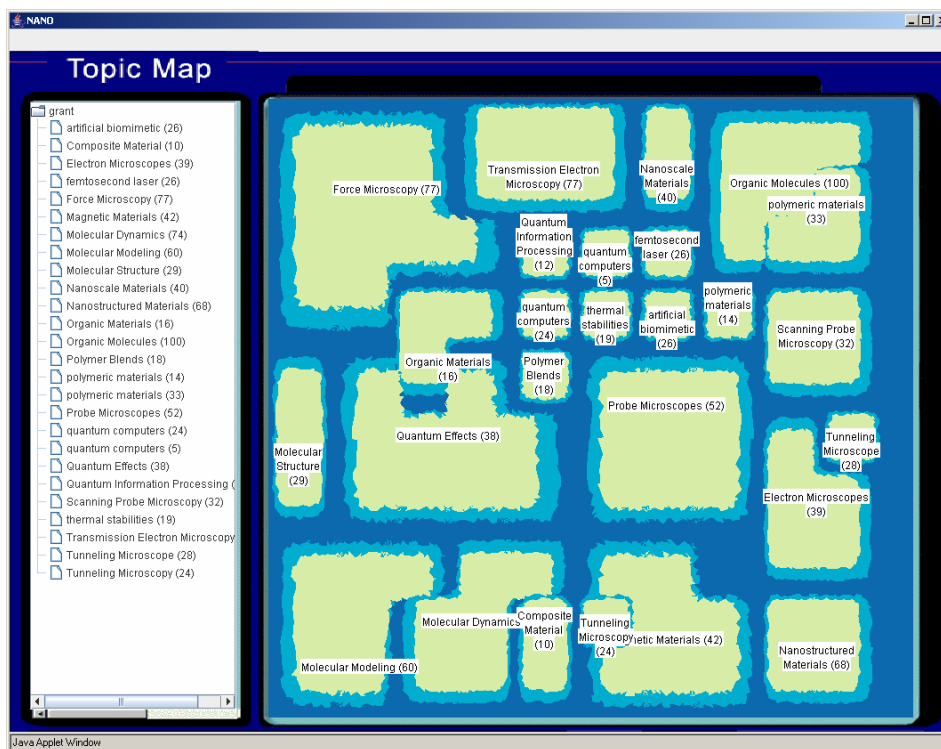


Figure 3. NSE new award content map (2001-2002)

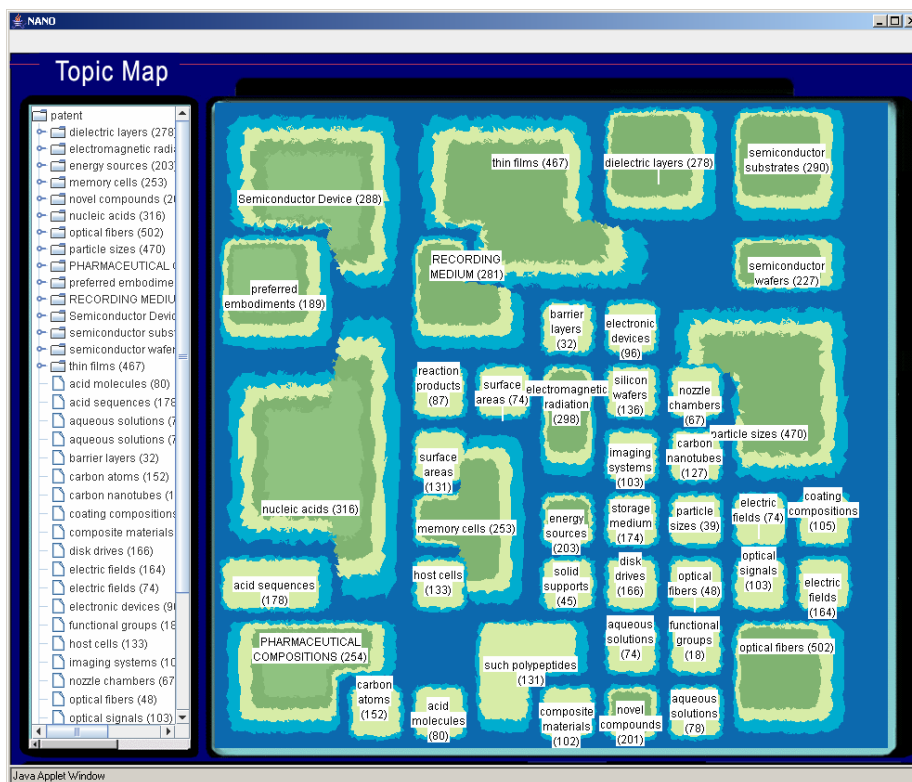


Figure 4. NSE patent content map (2001-2002)

Topic Map Analysis for 2003-2004

Figure 5 presents the award content map for the years between 2003 and 2004. With the color scheme described previously, Figure 5 displays many new award topics (shown as red regions) during 2003-2004, for instance, “condensed matter physics,” “electronic devices,” “optical properties,” and “liquid crystal.” The “microscope”-related, “quantum”-related and “molecular”-related topics are still active. The detailed topic region growth rates and base growth rate are presented in Table 10.

Figure 6 presents the colored patent content map of the same time period. The dominant patent topics were “pharmaceutical compositions,” “semiconductor devices,” “optical fibers,” “nucleic acids,” “carbon nanotubes,” and “dielectric layers.” New patent topics include “metal oxides,” “magnetic layers,” “conductive materials,” “laser beams,” “amino acid sequences,” “refractive indexes,” and “silicon substrates.” Table 11 presents the detailed growth rate information. Similar to the topic areas in the award content map, many patent topic areas were new or had a higher growth rate than the base rate, indicating that the patents issued in 2003-2004 were dominated by new and growing topic areas.

Optical devices	19	0	N/A
Optical Properties	66	0	N/A
Organometallic Chemistry	80	0	N/A
Quantum Dots	94	0	N/A
Quantum Information	25	0	N/A
Scanning Electron Microscopes	45	0	N/A
Self-assembly processes	42	0	N/A
Magnetic Materials	40	42	-0.05
Molecular Dynamics	40	74	-0.46
Molecular Modeling	44	60	-0.27
Molecular Structure	32	29	0.10
Nanostructured Materials	115	68	0.69
<i>Baseline Growth Rate</i>			<i>0.631</i>

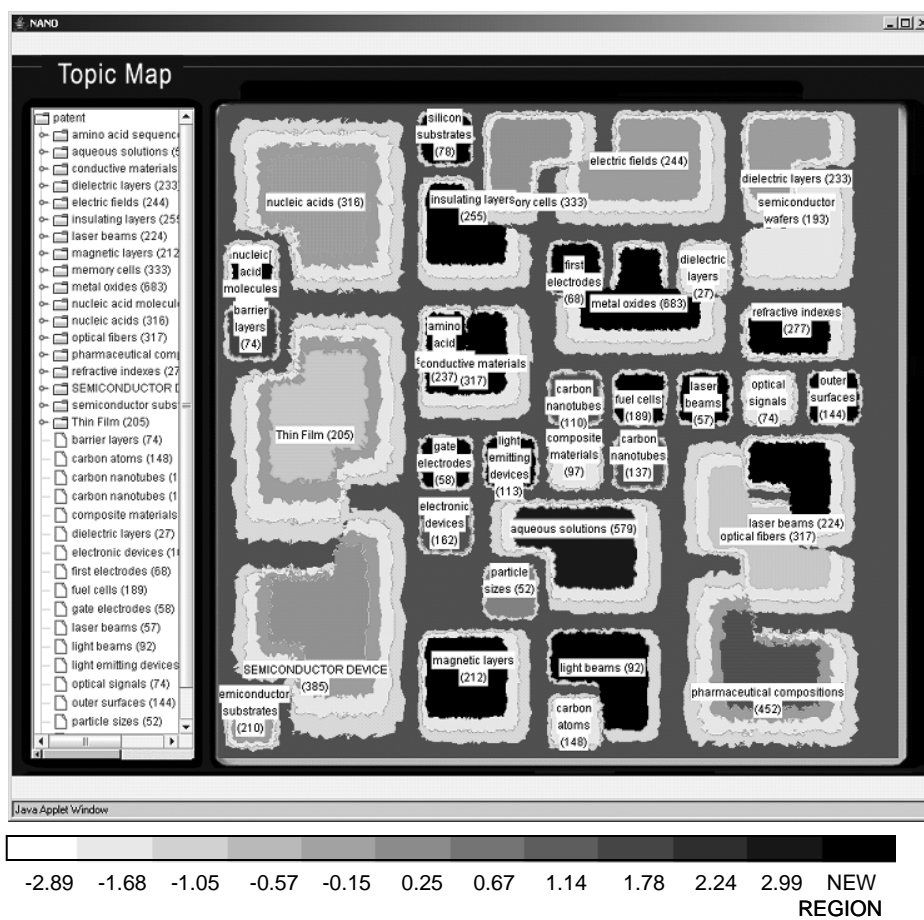


Figure 6. NSE patent content map (2003-2004)

Table 11. NSE patent changes from (2001-2002) to (2003-2004)

Region Label	# of Patents in the region (2003 - 2004)	# of Patents in the region (2001 - 2002)	Growth Rate
amino acid sequences	237	0	N/A
conductive materials	317	0	N/A
first electrodes	68	0	N/A
fuel cells	189	0	N/A

gate electrodes	58	0	N/A
insulating layers	255	0	N/A
laser beams	281	0	N/A
light beams	92	0	N/A
light emitting devices	113	0	N/A
magnetic layers	212	0	N/A
metal oxides	683	0	N/A
nucleic acid molecules	220	0	N/A
outer surfaces	144	0	N/A
refractive indexes	277	0	N/A
silicon substrates	78	0	N/A
barrier layers	74	32	1.31
electronic devices	162	96	0.69
composite materials	97	102	-0.05
optical signals	74	103	-0.28
carbon nanotubes	247	127	0.94
carbon atoms	148	152	-0.03
aqueous solutions	579	178	2.25
semiconductor wafers	193	227	-0.15
electric fields	244	238	0.03
memory cells	333	253	0.32
pharmaceutical compositions	452	254	0.78
dielectric layers	260	278	-0.06
semiconductor device	385	288	0.34
semiconductor substrates	210	290	-0.28
nucleic acids	316	316	0.00
Thin Film	205	467	-0.56
particle sizes	52	509	-0.90
optical fibers	317	550	-0.42
<i>Baseline Growth Rate</i>			<i>0.046</i>

One observes that among all the 33 topics of the patents published in 2003-2004, 15 were new topics. Among all the 29 topics of the awards issued in 2003-2004, 24 were new topics. The baseline growth rate of awards issued in 2003-2004 was 0.631, which is significantly higher than that of patents published in 2003-2004 (0.046). The topics in NSF awards changed at a faster rate than the topics in USPTO patents. This could indicate that changes of topics of new awards were “upstream” of the changes of topics in patents.

5. Patent/inventor Impact Analysis

In this section we analyze the patents’ and inventors’ impact of NSE research reflected in the patent citation data. We assess the evolution of the impact of the patents published in different years. We also compare different comparison groups of patents and inventors to assess the impact of different funding resources. Details regarding the complete NSE patent dataset can be found in our previous paper (Huang et al., 2004).

Measures

We use the number of times an inventor/patent is cited by others (number of cites) to measure its impact. This measure was initially used in the evaluation of academic publications. The idea is that citation implies an acknowledgement of authority on the part of the citing author to the cited one, and that an author's citation level reflects the community's perceived value of their contribution to the field. Based on a similar idea, the citations among patents also indicate the authority of patents and inventors in a technology field. In patent documents, the inventors are required by law to cite all important prior works on the pertinent topic. These citations eventually determine the scope of the monopoly power of that patent. Although the debates on the nature and quality of the citations in patent documents are still ongoing, the number of citations received by a patent/inventor has been the core measure in evaluating the impact and quality of patents/inventors and the technology competence of institutions and countries. In our study, the number of cites for a patent is the number of later patents from which this patent receives citations. The number of cites for an inventor is the sum of the number of cites of all his/her patents.

In our previous research, we also used a network structure-based authority score measure to evaluate patent/inventor impacts (Huang et al., 2003). As the 2001-2004 citation network is relatively sparse, such a measure is not suitable in this case.

Patent Citation Growth

To compare the impact of recent NSE research results with the previous years, we determined the citation growth of the NSE patents. Figure 7 shows the average number of cites for the patents published in 2001-2004. In this figure, we have included the 1991-2000 patent data for comparison purposes. We can observe that there are steady increases in the average numbers of cites after the patents' publication. In this graph, the slopes of the lines indicate the speed of citation accumulation. Generally, the citation accumulation speed of recently published patents is faster than that of the older patents and the patents published in 2001-2004 follow this pattern. The more recent patents clearly have greater impact on future patents. Figure 8 details the average number of cites for the patents published between 2001 and 2004, which are also included in Figure 7. In these four years, the patents have quite similar citation accumulation trends.

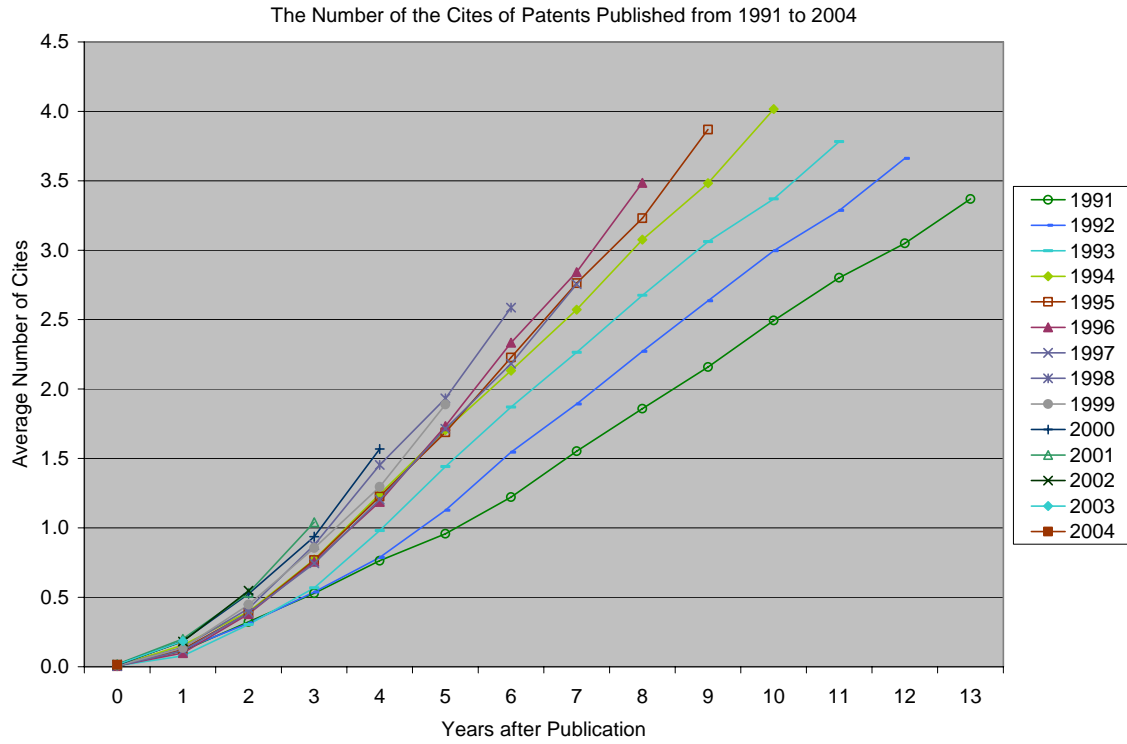


Figure 7. Average number of cites for patents published between 1991 and 2004

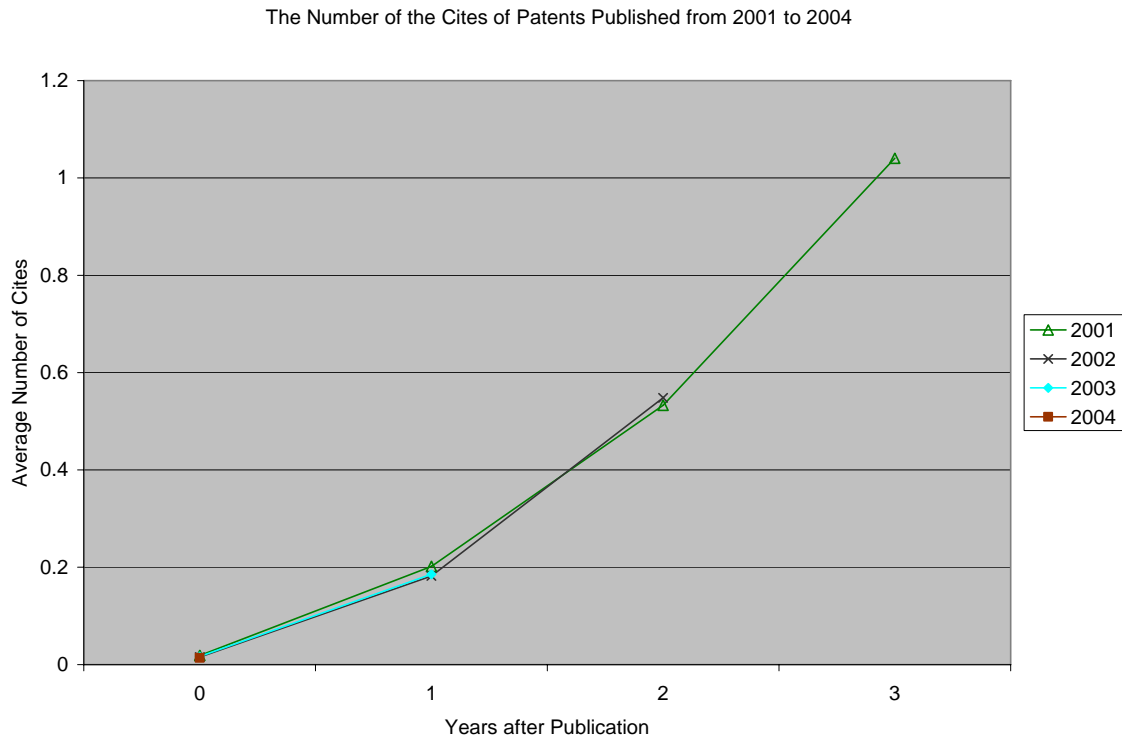


Figure 8. Average number of cites for patents published between 2001 and 2004

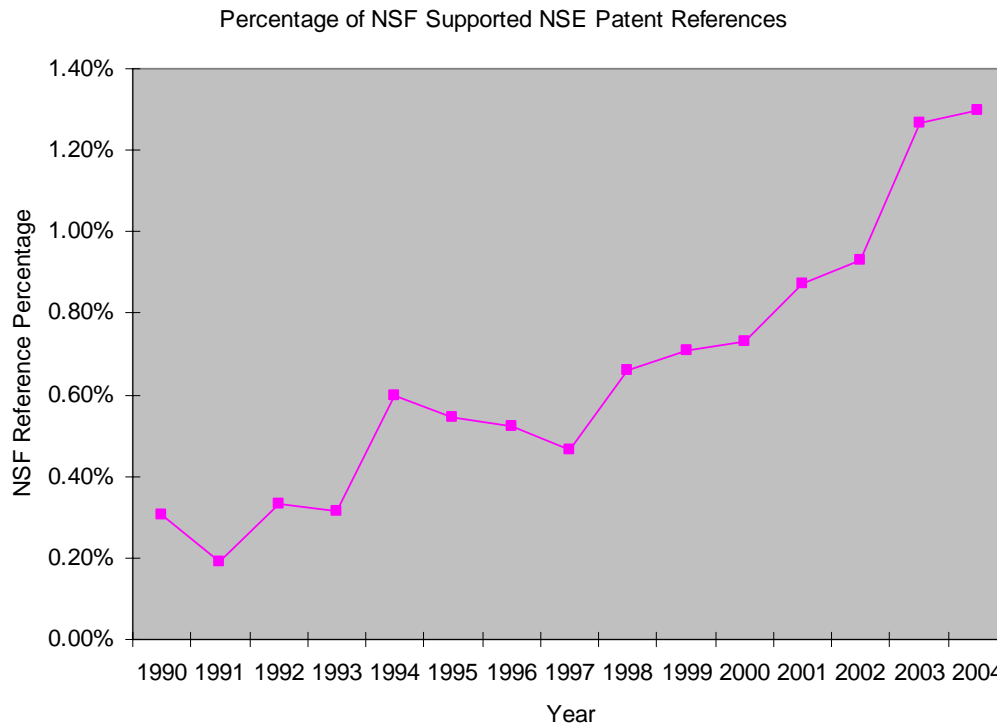


Figure 9. Percentage of NSF supported patents in the references of NSE patents

The percentage of the NSF patents cited by the NSE patents in each year is shown in Figure 9. One can observe that there is an increasing trend of the percentage of NSF supported patents in all the patents cited by NSE patents from 0.71% in 2000 to about 1.30% in 2004.

Comparison of the Impact of Different Groups

In order to compare the impact of publicly funded research by NSF and the impact of other kinds of funding resources, we have formed nine comparison groups similar as Huang et al. (2003, 2004):

1. NSF: PI-inventors and their patents
2. IBM: Inventors and patents of IBM
3. Top10: Inventors and patents of top 10 institutions
4. UC: Inventors and patents of the University of California
5. US: Inventors and patents of the United States
6. EntireSet: Inventors and patents of the entire patent dataset
7. Japan: Inventors and patents of Japan
8. European: Inventors and patents of European countries
9. Others: Random inventors and patents of countries other than the U.S., Japan, and European countries

Among these nine groups, only the NSF group represents a public funding source. The IBM group, which is the biggest assignee institution, represents the top commercial

funding sources. The UC group, which is the biggest academic assignee institution, represents the top funding sources through academic channels. The U.S., Japan, and European groups are the main countries/regions in the NSE field. The Top10 group represents the main research institutions in the NSE field after the number of patents.

To assess the detailed status of the critical patents/inventors in recent years, we compared different groups' patents/inventors over three time periods:

1. Patents published from 2001 to 2004
2. Patents published from 2001 to 2002
3. Patents published from 2003 to 2004

For the patents published between 2001 and 2002, the patents' numbers of cites can be calculated in two ways: (1) *restricted citation*: only the citations from patents issued in the same two years 2001-2002 are counted; (2) *extended citation*: all patents issued between 2001 and 2004 that cited 2001-2002 patents are counted.

As we have three time periods for comparison, it should be noticed that the Top10 assignee institutions are different in different time periods, which is shown in Table 12.

Table 12. Top 10 assignee institutions

Rank	Assignee Name	Number of Patents
2001-2004		
1	International Business Machines Corporation	730
2	Micron Technology, Inc.	620
3	Advanced Micro Devices, Inc.	519
4	The Regents of the University of California	461
5	Minnesota Mining and Manufacturing Company	396
6	Xerox Corporation	356
7	Intel Corporation	268
8	General Electric Company	239
9	NEC Corporation	234
10	Motorola, Inc.	227
2001-2002		
1	International Business Machines Corporation	381
2	Micron Technology, Inc.	285
3	Advanced Micro Devices, Inc.	235
4	The Regents of the University of California	212
5	Minnesota Mining and Manufacturing Company	204
6	Xerox Corporation	191
7	NEC Corporation	149
8	Motorola, Inc.	116
9	Canon Kabushiki Kaisha	115
10	Silverbrook Research PTY LTD	115
2003-2004		
1	International Business Machines Corporation	349
2	Micron Technology, Inc.	335
3	Advanced Micro Devices, Inc.	284
4	The Regents of the University of California	249
5	Intel Corporation	196

6	Minnesota Mining and Manufacturing Company	192
7	Xerox Corporation	165
8	Hewlett-Packard Development Company, L.P.	162
9	General Electric Company	138
10	Eastman Kodak Company	133

Statistical Analysis

We conducted a series of statistical hypothesis tests to compare the nine groups' impact in four settings: 2001-2004, 2001-2002 restricted citation, 2001-2002 extended citation, and 2001-2004. We have statistically verified when the hypothesis that PI-inventors and their patents had higher impact on the NSE field than other groups of inventors and their patents in recent years is true.

Hypotheses on the impact of patents (Figure 10):

1a: Patents associated with PI-inventors had a higher number of cites measure than patents associated with other groups of inventors during 2001-2004.

1b: Patents associated with PI-inventors had a higher number of cites measure than patents associated with other groups of inventors during 2001-2002, if we restricted the citing patents to those published between 2001 and 2002.

1c: Patents associated with PI-inventors had a higher number of cites measure than patents associated with other groups of inventors during 2001-2002, including all citing patents published between 2001 and 2004.

1d: Patents associated with PI-inventors had a higher number of cites measure than patents associated with other groups of inventors during 2003-2004.

Hypothesis on the impact of inventors (Figure 11):

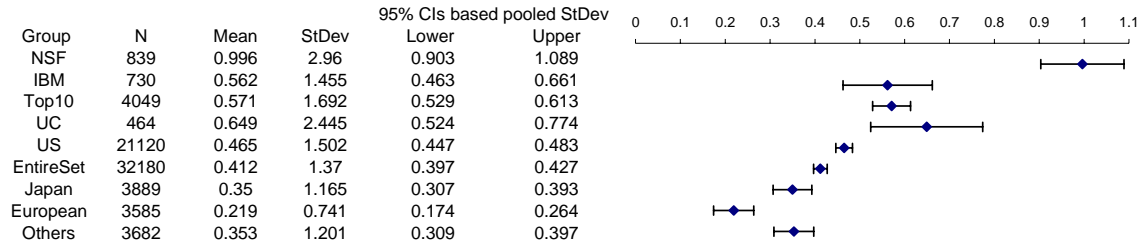
2a: PI-inventors had a higher number of cites measure than other groups of inventors during 2001-2004.

2b: PI-inventors had a higher number of cites measure than other groups of inventors during 2001-2002, if we restricted the citing patents total to those published between 2001 and 2002.

2c: PI-inventors had a higher number of cites measure than other groups of inventors during 2001-2002, including all citing patents published between 2001 and 2004.

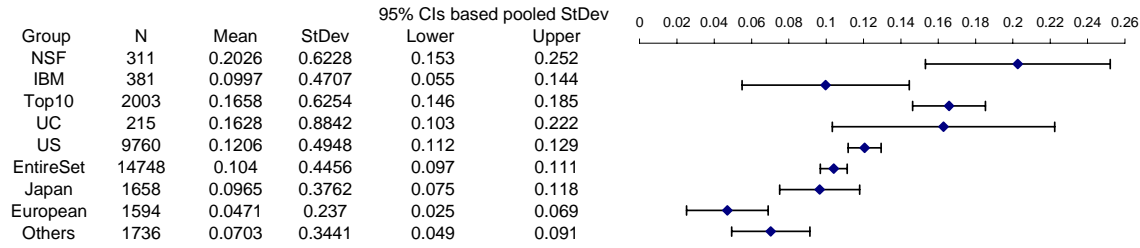
2d: PI-inventors had a higher number of cites measure than other groups of inventors during 2003-2004.

We conducted ANOVA tests according to our eight hypotheses and analysis results are presented in Figures 10 and 11.



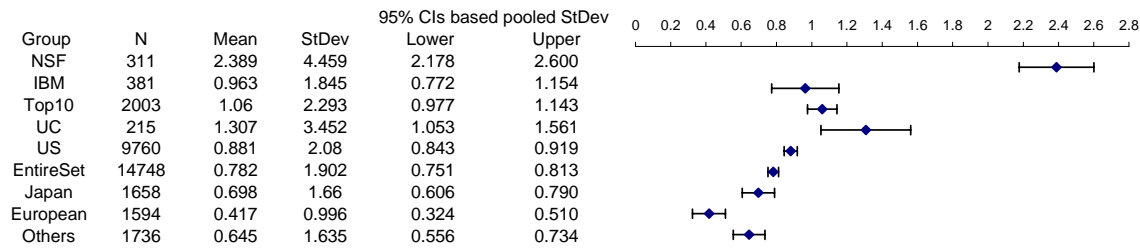
Pooled StDev = 1.428

(1a) Number of cites – patent 2001-2004



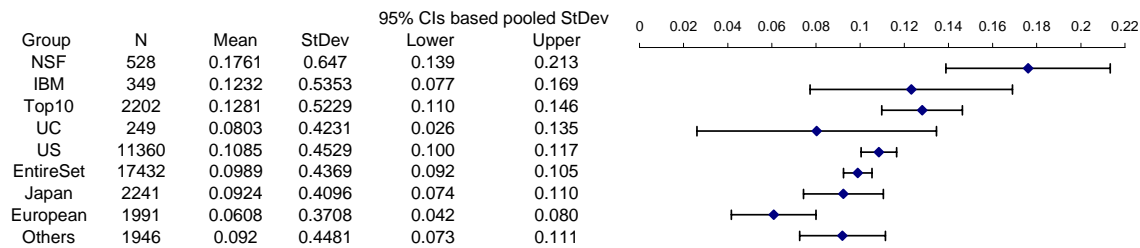
Pooled StDev = 0.4649

(1b) Number of cites – patent 2001-2002 with “restricted citation”



Pooled StDev = 1.979

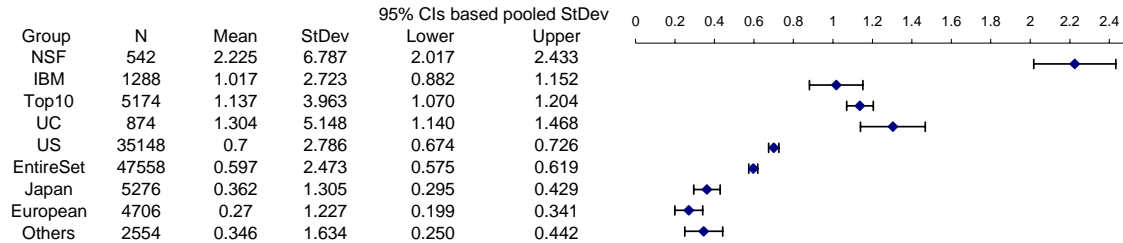
(1c) Number of cites – patent 2001-2002 with “extended citation”



Pooled StDev = 0.4474

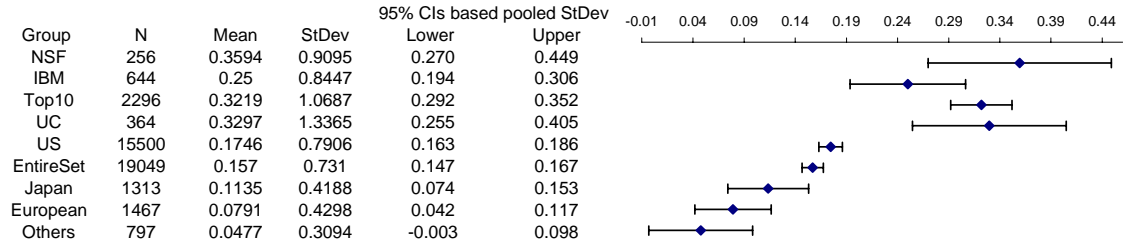
(1d) Number of cites – patent 2003-2004

Figure 10. ANOVA results for hypothesis testing for citations per patent



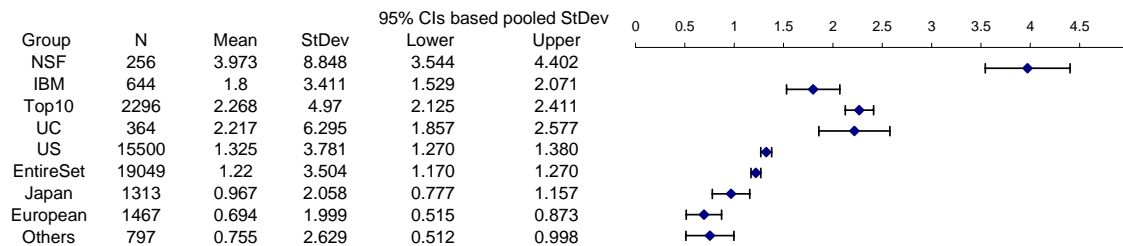
Pooled StDev = 2.652

(2a) Number of cites – inventor 2001-2004



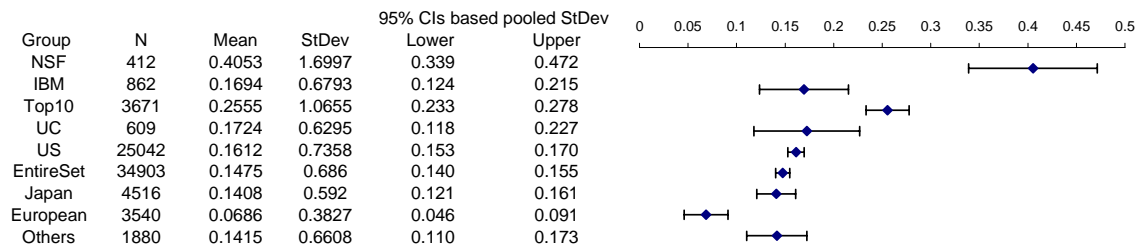
Pooled StDev = 0.7649

(2b) Number of cites – inventor 2001-2002 with “restricted citation”



Pooled StDev = 3.701

(2c) Number of cites – inventor 2001-2002 with “extended citation”



Pooled StDev = 0.7177

(2d) Number of cites – inventor 2003-2004

Figure 11. ANOVA results for hypothesis testing for citations per inventor

Figure 10(1a) shows that the respective hypothesis was supported at the 95% level. In the interval 2001 to 2004, NSF-funded PI-inventors’ patents have a significantly larger number of cites measure (about 1) than patents in other comparison groups such as IBM (0.56), Top10 (0.57), UC (0.64), and US (0.46). These four groups’ average number of

cites are significantly larger than the EntireSet average (0.41), while the Japan (0.35), European (0.22) and Other (0.34) groups have a smaller-than-average number of cites.

Figure 10(1b) shows that the respective hypothesis was not supported at the 95% level. During 2001 to 2002, with the restricted citations only to those two years, there is no significant difference in the number of cites measure for the comparison groups NSF (0.17), Top10, and UC. But these groups' numbers of cites are significantly larger than the European group and Others group.

Figure 10(1c) shows that the hypothesis was supported at the 95% level. During 2001 to 2002, with the extended count of number of cites, NSF-funded PI-inventors' patents have a significantly larger number of cites than patents in other comparison groups, followed by the groups IBM, Top10, UC, US, and EntireSet. The Japan and Others groups had a significantly smaller number of cites than these five groups and a significantly larger number of cites than the European group.

Figure 10(1d) shows that the hypothesis was not supported at the 95% level. During 2003 to 2004, there is no significant difference in the number of cites measure of the comparison groups NSF, IBM, Top10, and UC. But the NSF group's number of cites is significantly larger than the US, EntireSet, Japan, Others, and European groups.

The hypothesis in Figure 11(2a) was supported at the 95% level. During 2001 to 2004, NSF-funded PI-inventors have a significantly higher number of cites measure than inventors in other comparison groups, followed by the groups IBM, Top10, and UC. The US group had a significantly smaller number of cites than these three groups and a significantly larger number of cites than the EntireSet group. The Japan, Others, and European groups had a significantly smaller number of cites compared to other groups.

The hypothesis in Figure 11(2b) was not supported at the 95% level. During 2001 to 2002, with the restricted count of number of cites, there is no significant difference in the number of cites measure of the comparison groups NSF, IBM, Top10, and UC. But these five groups' numbers of cites are significantly larger than the US, EntireSet, Japan, European, and Others groups.

The hypothesis in Figure 11(2c) was supported at the 95% level. During 2001 to 2002, with the non-restricted count of number of cites, NSF-funded PI-inventors have significantly higher number of cites measures than inventors in other comparison groups, followed by the groups IBM, Top10, and UC. The US group had a significantly smaller number of cites than these three groups and a significantly larger number of cites than the EntireSet group. The Japan, Others, and European groups had a significantly smaller number of cites compared to other groups.

The hypothesis in Figure 10(2d) was supported at the 95% level. During 2003 to 2004, NSF-funded PI-inventors have significantly higher number of cites measures than inventors in other comparison groups, followed by the Top10 group. The IBM, UC, US, EntireSet, Japan, and Others groups had a significantly smaller number of cites than the

NSF and Top10 group. The European group had a significantly smaller number of cites compared to other groups.

Table 13. Hypotheses testing results

Hypotheses	Patent	Inventor
2001-2004	1a ✓	2a ✓
2001-2002(restricted citation)	1b ×	2b ×
2001-2002 (extended citation)	1c ✓	2c ✓
2003-2004	1d ×	2d ✓

Table 13 summarizes the hypotheses testing results. As hypotheses 1a and 2a are supported, we can conclude that PI-inventors and their patents have higher impact than the inventors and their patents in other groups from 2001-2004. As hypotheses 1b and 2b are not supported, for patents published in 2001-2002 only considering the citing patents published in 2001-2002, PI-inventors do not have significantly higher impact than other groups. As hypotheses 1c and 2c are supported, we can conclude that PI-inventors and their patents are more influential than the inventors and their patents in other groups in 2001-2002 as time passes, considering the impact throughout 2001-2004. Only considering the patent citations in a two-year period may be too short to differentiate different patents' impacts. In the test on the third time period, 1d is not supported, which is consistent with the 2001-2002 results. But 2d is supported, which indicates that PI-inventors had exceptionally strong influence on NSE patents in 2003-2004. Significantly larger numbers of cites for PI-inventors than other groups were observed even within the two-year time period. In general, we observe that it is difficult to differentiate the influence level of inventor groups in short time periods such as 1-2 years. As the life of a patent increases, the NSF's PIs impact generally increases over other groups that may be explained by the fundamental research usually sponsored by the NSF that has longer influence

6. Conclusions

The NSF support of NSE research awards in the interval 2001-2004 and its impact on technological innovation, as described by the USPTO patent dataset, have been evaluated in this paper using: trend analysis, topic map analysis, and inventor/patent impact analysis. Key findings are:

- The rate of increase in the number of NSF awards and USPTO patents in the NSE field in 2001-2004 is higher than the respective averages. The percentage of NSE patents has increased from 3.8% to 4.9% if patents are keyword searched by “full-text” (including NSE patent claims and use of NSE tools) and from about 0.66% to about 1.09% if searched by “title-claims” search (including NSE claims only). The corresponding percentage of NSF active awards with full or partial NSE contents increased from 6.0% in 2001 to 8.4% in 2004.
- The NSE topics in both patents and NSF awards changed significantly in only four years. NSF awards covered a smaller number of topics than the USPTO patents in the NSE field (26 versus 37 in 2001-2002 and 29 versus 33 in 2003-2004). NSF

relatively covered the topics related to microscopy, quantum effects, and molecular study areas. NSF awards covered fewer biology-related and pharmaceutical-related topics than USPTO patents did. But the NSE topics of the NSF awards changed faster than those of the USPTO patents in terms of the percentage of new topics and the baseline growth rate of the topics (see Figure 6 versus Figure 5), indicating the NSF projects would respond faster to the changing research interest in the field.

- The number of cites of the patents published from 2001 to 2004 accumulated faster than that of patents before 2001, indicating the higher impact of the recently published patents. The 2003-2004 NSE patents cited more NSF supported patents than the 2001-2002 NSE patents. More than 1.2% of the references of the NSE patents published in 2003 to 2004 were supported by NSF as compared to 0.5% in 1997 and 0.9% in 2000.
- From 2001 to 2004, the NSF's PI-inventors and their patents had more influence than the inventors and patents in other groups based on the "number of cites" measure (see 1a and 1d in Figure 10, and 2a and 2d in Figure 11), and this influence increases after the patent publication (see 1c and 1b in Figure 10, and 2b in Figure 11) suggesting the importance of fundamental research in longer term. The number of cites per NSF's PI-inventor is 2.2 as compared to 0.6 for the entire set in the interval 2001-2004.
- In the short term (1-2 years), it is generally difficult to differentiate the influence level of inventor groups. However, in a two-year period, NSF's PI-inventors had a significantly stronger influence (about twice) on the NSE domain than the entire set in 2003-2004 (see 1d in Figure 10 and 2d in Figure 11).

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