

Longitudinal nanotechnology development (1991–2002): National Science Foundation funding and its impact on patents

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Abstract

Nanotechnology holds the promise to revolutionize a wide range of products, processes and applications. It is recognized by over sixty countries as critical for their development at the beginning of the 21st century. A significant public investment of over \$1 billion annually is devoted to nanotechnology research in the United States. This paper provides an analysis of the National Science Foundation (NSF) funding of nanoscale science and engineering (NSE) and its relationship to the innovation as reflected in the United States Patent and Trade Office (USPTO) patent data. Using a combination of bibliometric analysis and visualization tools, we have identified several general trends, the key players, and the evolution of technology topics in the NSF funding and commercial patenting activities. This study documents the rapid growth of innovation in the field of nanotechnology and its correlation to funding. Statistical analysis shows that the NSF-funded researchers and their patents have higher impact factors than other private and publicly funded reference groups. This suggests the importance of fundamental research on nanotechnology development. The number of cites per NSF-funded inventor is about 10 as compared to 2 for all inventors of NSE-related patents recorded at USPTO, and the corresponding Authority Score is 20 as compared to 1.8.

Introduction

Nanotechnology is expected to have broad and fundamental implications on many sectors of the economy. Advances in nanoscale science and engineering (NSE) have already affected a wide range of research and education areas, and it is changing industry on an accelerating path. It promises to create interdisciplinary research and development (R&D) platforms for industry and medicine, and to

address revolutionary applications such as detecting and treating diseases, efficient monitoring and protecting the environment, producing and storing energy, and building complex structures for electronic circuits or airplanes. Public funding has been playing an important role in fostering related research, development and educational activities. In 2000 the United States announced the *National Nanotechnology Initiative* (NNI, <http://www.nano.gov>) based on a long-term vision (Roco et al.,

2000). Between 2000 and 2004, nanotechnology has been recognized as a national priority by all industrialized countries and many developing countries. This was stimulated in part by the NNI unveiled by then President Clinton in January 2000. In December 2003 President Bush signed into law the *21st Century Nanotechnology R&D Act*, which authorizes \$3.7 billion funding for nanotechnology R&D in several agencies for fiscal years 2005–2008. This legislation puts into law the NNI programs and activities, and provides guidance for enhancing innovation and responsible development of the field. The U.S. Nanoscale Science, Engineering and Technology Subcommittee (NSET) of the National Science and Technology Council has recently published its second long-term NNI strategic plan (NSET, 2004).

Significant public funding has been provided for nanotechnology R&D beginning with 1991 and at a higher level after 2001. It is necessary to understand how funding has impacted the activities in the field. Scientific evaluation of implications of public funding on R&D output and the overall development in a scientific and engineering field is a complex task (Adams & Criliches 1998). Only sparse literature exists on this topic. Most previous studies have focused on the impact of public funding on scientific publications. Adams and Criliches (1998) have identified a strong correlation between research output and research funding, while Arora and Gambardella (1998) reported a moderate effect of NSF funding on research output. In these studies, the research output is typically measured by the number of published scientific papers and citations these papers receive. A later study by Payne and Siow (2003) showed that \$1 million in federal research funding for a research university on average resulted in 11 more articles, 0.2 more patents, and \$411,000 more in total faculty salaries. Based on the citation to scientific literature in patent documents, Narin (1998) addressed the impact of research output on the commercial technology development of a field. His study showed that roughly 73% of all papers cited on the front page of U.S. industry patents had their origins in publicly funded projects, indicating critical impact of funded scientific research on commercial technology development. Narin also concluded that the impact of public funding varies across different technology fields.

This paper presents an analysis of NSF (<http://www.nsf.gov/nano>) funding activities in the NSE field and their relationship to the commercial technology development as reflected in the patent data from the USPTO. Instead of using scientific publication data, as most previous studies did, we analyze funding awards and patent documents, as well as citation and other connections among them. This provides a more direct account of the impact of public funding on technological innovation. We apply information visualization techniques to map the relevant technology topic areas and visualize the citation networks. Advanced network analysis techniques are applied to provide more accurate assessment of impacts based on the patent citation network.

The first part of this paper describes the NSE-related award and patent datasets. Then, the topic areas of the awards and patents are compared using award/patent content map visualization and citation networks for three successive time periods between 1991 and 2002. Finally, we present the impact of NSF-funded researchers on nanotechnology development using the analysis of critical patents and inventors, as well as statistical comparison of the impact of NSF-funded researchers with other groups of inventors.

Basic analysis of award and patent data

We have used keywords according to the National Nanotechnology Initiative definition of nanotechnology to identify the awards and patents that have partial or full contents in NSE. The keywords are the same as those used in previous work (Huang et al., 2004). The search has been performed on two public databases: the NSF awards (title and summary) and USPTO patent documents (full text). The NSF investment in nanotechnology represents about 1/3 of the federal government funding in the United States and about 1/12 worldwide government funding, and it is focused on long-term research and education goals.

Bibliometric analysis has been applied on the resulted NSE-related award and patent datasets. Temporal evolution patterns and key linkages between the NSE-related awards and NSE-related patents have been identified. Three time intervals have been considered in this study:

- 1991–1995 (5 years). 1991 corresponds to the beginning of the first program solicitation focused on nanoparticle synthesis and processes at NSF. Other funding programs began during this time interval such as the National Nanotechnology User Network (NSF, 1994) and instrumentation for nanotechnology (NSF, 2005).
- 1996–2000 (5 years). The U.S. nanotechnology interagency working group was established in 1996, followed by the worldwide study on Nanostructure Science and Engineering in 1997 (Siegel et al., 1999), and NSF program announcements on Functional Nanostructures in 1997–1998 (NSF 1997).
- 2001–2002 (2 years). These are the first two years of NNI, marked by an increased annual funding of nanotechnology R&D.

The number of NSE-related awards and patents per time interval are:

- Interval 1991–1995: NSF made 1,146 NSE-related awards and USPTO issued 11,021 NSE-related patents
- Interval 1996–2000: 2,384 awards and 23,057 patents
- Interval 2001–2002: 1,733 awards and 14,748 patents.

Award data

The NSF funds research and education in science and engineering through awards (grants, contracts, and cooperative agreements). The foundation accounts for about 20 percent of federal support to academic institutions for basic research (<http://www.nsf.gov/home/grants.htm>). About 6% of NSF budget in its 2005 budget is dedicated to NSE. The dataset for all science and engineering fields includes 122,778 awards in the interval 1991–2002 under 65 NSF Divisions and 638 Programs involving 81,040 investigators. The awards can be accessed at <http://www.nsf.gov/awardsearch/index.jsp>. A complete list of NSF Divisions, Directorates, and Programs is available at <http://www.nsf.gov/home/nsforg/orglist.htm>. The keyword search was performed for the title and summary of each award that are available on the public website. The detailed list of keywords can be found in our previous publications (Huang et al., 2003, 2004).

We have identified 5,263 NSE-related NSF awards involving 38 Divisions and 245 Programs between 1991 and 2002. Tables 1 and 2 present the top NSF Divisions and Programs with the largest numbers of NSE-related awards during 1991–2002 and during the three time intervals. The Division of Materials Research (DMR) was the dominant Division with more than a quarter of the total number of NSE-related awards, followed by the Division of Chemistry (CHE), Division of Chemical and Transportation Systems (CTS), Division of Design, Manufacture and Industrial Innovation (DMI), and Division of Electrical and Communication Systems (ECS). The top 5 NSF Programs funding the NSE research during 1991–2002 are: Electronics, Photonics, and Device Technologies (Program # 1517), Condensed Matter Physics (# 1710), Small Business Phase I (# 5371), Polymers (# 1773), and Major Research Instrumentation (# 1189).

Patent data

The USPTO patent documents have been “full-text” searched (title, abstract, claims, and specifications) by the NSE keywords. The resulted dataset includes both the patents having nanotechnology products (generally identified by keywords in the “title-claims”) and those using the nanoscale science and engineering tools (generally identified in the specifications). The full-text search resulted in 48,826 NSE-related patents issued during 1991 to 2002. There are 14,959 assignees, 50,071 inventors, 89 countries, and 402 first-level United States Patent Classification categories out of 423 in total associated with these NSE-related patents. Huang et al. (2004) provided a detailed analysis of contributing countries, institutions, and technology fields in NSE in this dataset.

The total numbers of patents issued to top assignee countries between 1991 and 2002 are listed in Table 3. The United States produced the majority of the NSE-related patents, followed by Japan, Germany, France, and Canada.

The numbers of NSE-related patents by the top 20 assignees institutions are shown in Table 4. The top five assignees for the interval 1991–2002 are International Business Machines Corporation

Table 1. Top 20 NSF divisions funding the NSE research: Number of new awards per year (1991–2002)

Division	Number of awards			
	1991–2002	1991–1995	1996–2000	2001–2002
DMR, Division of Materials Research	1443	335	686	422
CHE, Division of Chemistry	715	196	326	193
CTS, Div of Chemical and Transport Systems	533	102	254	177
DMI, Div of Design, Manufac & Industrial Innov	501	82	209	210
ECS, Div of Electrical and Communications Sys	408	91	153	164
INT, Office of Internatl Science & Engineering	216	56	103	57
DUE, Division of Undergraduate Education	191	80	84	27
CCR, Div of Computer-Communications Research	190	3	101	86
CMS, Div of Civil and Mechanical Systems	168	21	72	75
MCB, Div of Molecular and Cellular Bioscience	155	54	69	32
DBI, Div of Biological Infrastructure	98	27	56	15
BES, Div of Bioengineering & Environ Systems	97	8	37	52
DMS, Division of Mathematical Sciences	76	5	37	34
EAR, Division of Earth Sciences	65	12	24	29
EEC, Div of Engineering Education and Centers	62	9	25	28
PHY, Division of Physics	61	8	24	29
EIA, Division of Experimental & Integ Activit	43	2	15	26
OCE, Division of Ocean Sciences	38	17	12	9
IBN, Div of Integrative Biology and Neuroscie	29	3	18	8
EPS, Office of Exper Prog to Stim Comp Rsch	26	2	11	13

Table 2. Top 21 NSF programs funding the NSE research: Number of new awards per year (1991–2002)

Program	Number of awards			
	1991–2002	1991–1995	1996–2000	2001–2002
1517 Elect, Photonics, & Device Tec	319	65	121	133
1710 Condensed Matter Physics	305	83	144	78
5371 Small Business Phase I	253	51	113	89
1773 Polymers	224	65	98	61
1189 Major Research Instrumentation	160	0	64	96
1414 Interfac Trans, & TI Pro	155	36	74	45
1765 Materials Theory	153	30	73	50
4710 Des Auto For Micro & Nano Sys	150	0	92	58
1415 Particulate & Multiphase Process	136	23	62	51
7400 Undergrad Instrm & Lab Improve	124	72	52	0
1972 Electrochemistry & Surface Che	121	37	46	38
1725 Nat'l Facilities & Instrumtat	108	68	40	0
1715 Metals, Ceramics, & Elec Matr	106	67	39	0
1775 Electronic Materials	100	1	62	37
1750 Instrument for Materials Rsrch	99	1	57	41
1633 Surface Eng & Materials Design	94	13	43	38
1762 Solid-State Chemistry	94	4	48	42
1938 Chemical Instrumentation	82	21	48	13
5373 Small Business Phase II	69	7	36	26
1108 Instrumentat & Instrument Devp	66	23	37	6
1771 Metals	66	0	40	26

Table 3. Top assignee countries (1991–2002): Number of patents

Rank	Assignee country	Number of patents			
		1991–2002	1991–1995	1996–2000	2001–2002
1	United States	29968	6773	14183	9012
2	Japan	4890	1157	2232	1501
3	Federal Republic of Germany	3976	998	1927	1051
4	Canada	1321	300	606	415
5	France	1284	269	607	408
6	United Kingdom	551	135	272	144
7	China (Taiwan)	308	15	151	142
8	Israel	294	47	150	97
9	Switzerland	276	47	121	108
10	Australia	254	26	59	169
11	Republic of Korea	248	21	105	122
12	Italy	221	54	101	66
13	Netherlands	209	43	96	70
14	Sweden	154	23	59	72
15	Belgium	125	25	61	39
16	Denmark	92	18	41	33
17	Finland	75	8	36	31
18	Singapore	49	0	14	35
19	Norway	48	6	18	24
20	Austria	41	4	20	17

Table 4. Top assignee institution (1991–2002): Number of patents

Rank	Assignee name	Number of patents			
		1991–2002	1991–1995	1996–2000	2001–2002
1	International Business Machines Corporation	1103	226	509	368
2	Xerox Corporation	796	220	385	191
3	The Regents of the University of California	561	70	291	200
4	NEC Corporation	473	59	273	141
5	Eastman Kodak Company	465	173	206	86
6	Micron Technology, Inc.	461	13	167	281
7	Motorola, Inc.	447	139	206	102
8	Minnesota Mining and Manufacturing Company	395	158	236	1
9	Canon Kabushiki Kaisha	389	106	168	115
10	Kabushiki Kaisha Toshiba	313	53	174	86
11	Hitachi, Ltd.	302	84	134	84
12	Advanced Micro Devices, Inc.	298	3	74	221
13	Abbott Laboratories	292	110	141	41
14	Texas Instruments Incorporated	291	74	156	61
15	3M Innovative Properties Company	290	0	103	187
16	General Electric Company	289	98	100	91
17	Matsushita Electric Industrial Co., Ltd.	262	99	115	48
18	The United States of America as represented by the Secretary of the Navy	257	88	108	61
19	Genentech, Inc.	245	36	147	62
20	E. I. Du Pont de Nemours and Company	239	127	87	25

Table 5. Top US patent classification top-level technology fields (1991–2002)

Rank	Technology field	Number of patents			
		1991–2002	1991–1995	1996–2000	2001–2002
1	435: Chemistry: molecular biology and microbiology	6779	1097	3447	2235
2	514: Drug, bio-affecting and body treating compositions	5322	955	2840	1527
3	424: Drug, bio-affecting and body treating compositions	4197	666	2221	1310
4	536: Organic compounds – part of the class 532–570 series	3447	368	1856	1223
5	438: Semiconductor device manufacturing: process	3185	478	1261	1446
6	530: Chemistry: natural resins or derivatives; peptides or proteins; lignins or reaction products thereof	3172	579	1700	893
7	428: Stock material or miscellaneous articles	3136	660	1494	982
8	257: Active solid-state devices (e.g., transistors, solid-state diodes)	2922	758	1264	900
9	250: Radiant energy	2777	1020	1141	616
10	427: Coating processes	2434	585	1162	687
11	359: Optics: systems (including communication) and elements	2162	546	979	637
12	436: Chemistry: analytical and immunological testing	2151	597	985	569
13	430: Radiation imagery chemistry: process, composition, or product thereof	2113	569	971	573
14	356: Optics: measuring and testing	1825	553	891	381
15	422: Chemical apparatus and process disinfecting, deodorizing, preserving, or sterilizing	1298	325	576	397
16	204: Chemistry: electrical and wave energy	1217	310	559	348
17	546: Organic compounds – part of the class 532–570 series	1207	254	637	316
18	524: Synthetic resins or natural rubbers – part of the class 520 series	1169	282	538	349
19	252: Compositions	1147	308	532	307
20	210: Liquid purification or separation	1099	309	498	292

(IBM), Xerox Corporation, the University of California, NEC Corporation, and Eastman Kodak Company.

The technology fields correspond to the first-level United States Patent Classification categories (available at: <http://www.uspto.gov/go/classifica->

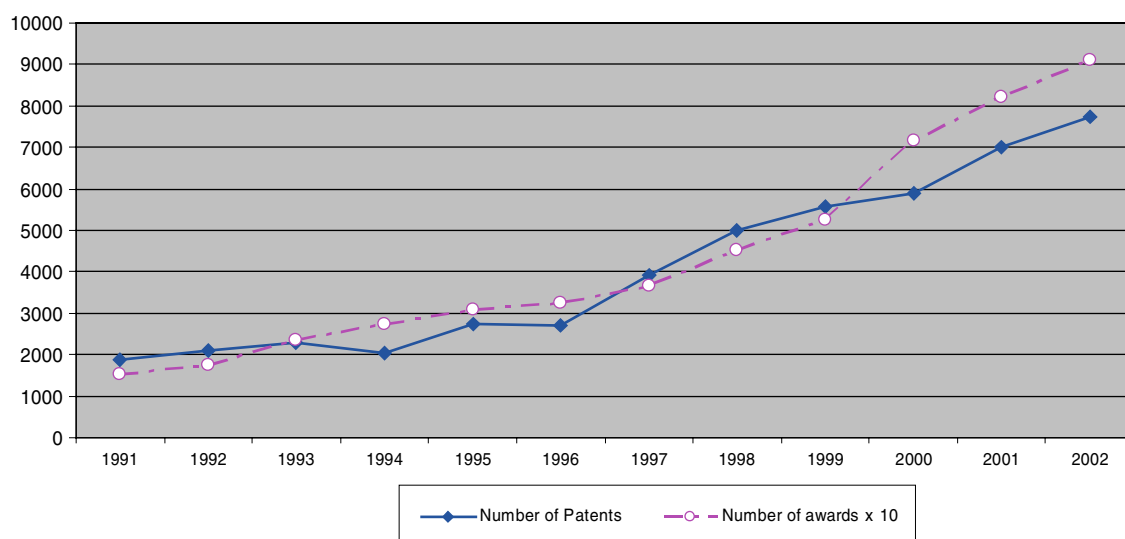


Figure 1. Trend analysis: the numbers of patents and new awards per year (1991–2002).

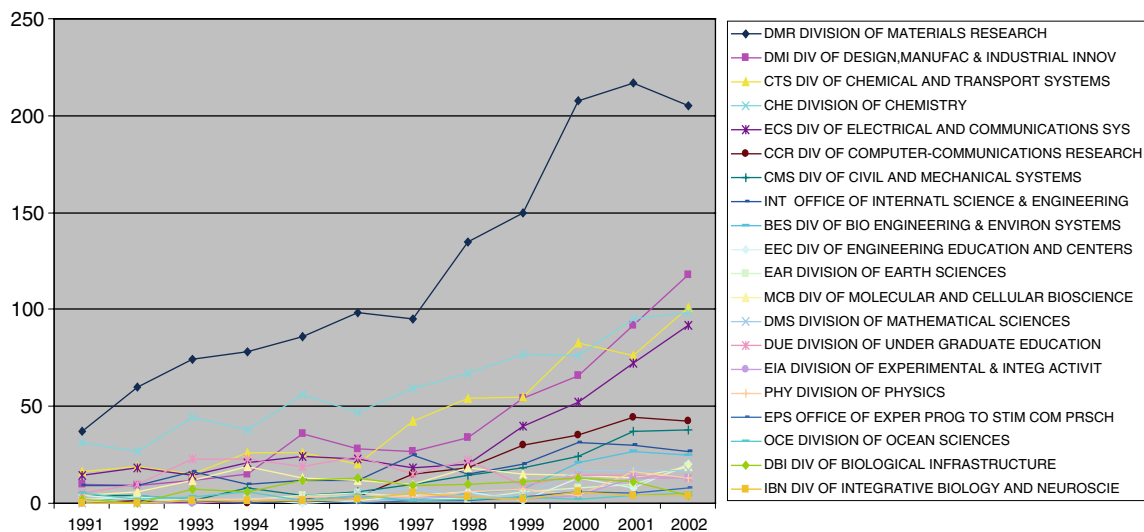


Figure 2. Trend analysis: number of awards per NSF division (1991–2002).

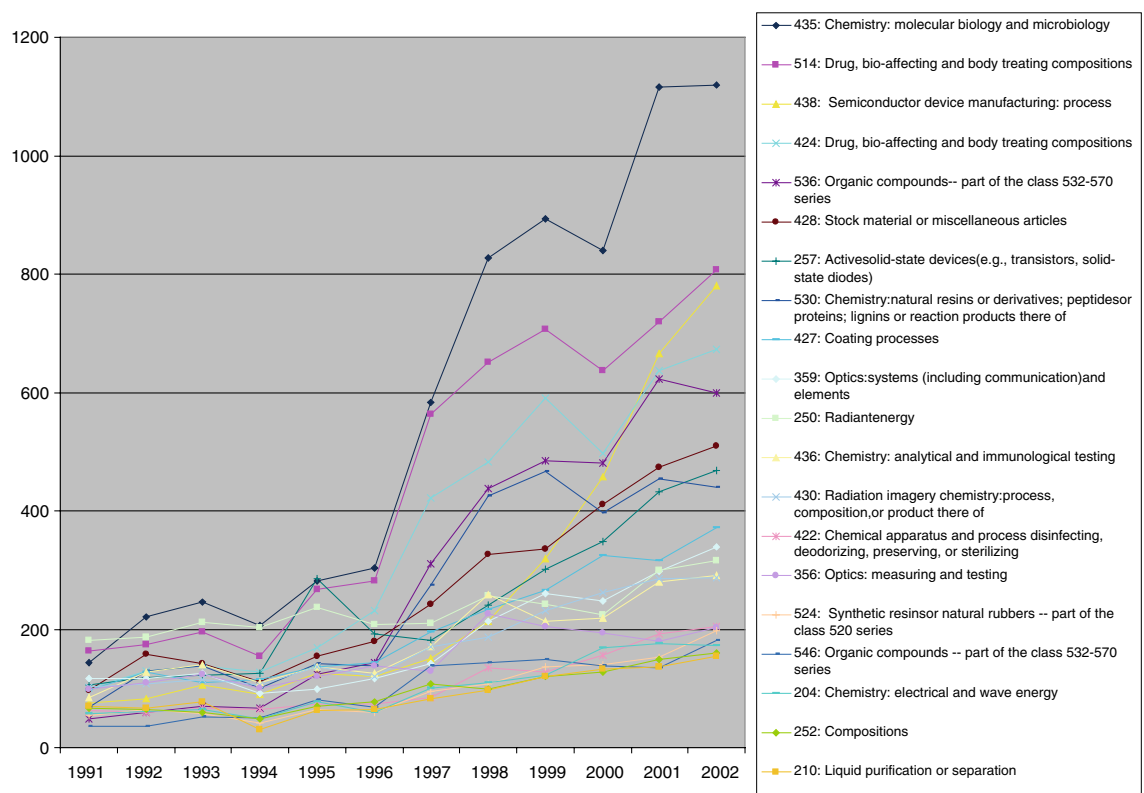


Figure 3. Trend analysis: Number of patents per technology field (1991–2002).

tion/ selectnumwithtitle.htm.) Some categories have identical names; however, the detailed specifications of such categories are different. We used

the category name as well as their assigned U.S. Patent Classification ID number to label each technology field.

Table 6. Top PI-inventors with the largest number of patents (1991–2002)

Rank	PI-inventors	Institution	Number of patent(s)
1	Pinnavaia, Thomas J.	Board of Trustees of Michigan State University	30
2	Whitesides, George M.	Harvard University	24
3	Lindsay, Stuart M.	Arizona Board of Regents acting on behalf of Arizona State University	18
4	Thompson, Mark E.	The Trustees of Princeton University	14
5	Asher, Sanford A.	University of Pittsburgh	14
6	Cantor, Charles R.	Boston University	14
7	Maris, Humphrey J.	Brown University Research Foundation	13
8	Fejer, Martin M.	Board of Trustees, Leland Stanford Junior University, Stanford University	12
9	Bard, Allen J.	Board of Regents, The University of Texas System	12
10	Hansma, Paul K.	Digital Instruments, Inc.	11
11	Klabunde, Kenneth J.	Kansas State University Research Foundation	11
12	Minne, Stephen C.	Board of Trustees of the Leland Stanford Jr. University	10
13	Searson, Peter C.	Candescent Technologies Corporation	10
14	Newkome, George R.	The University of South Florida	9
15	Kear, Bernard H.	Rutgers the State University of New Jersey	9
16	Bowers, John E.	CIENA Corporation	8
17	Rothschild, Kenneth J.	Amber Gen. Inc.	8
18	McCandlish, Larry E.	Exxon Research & Engineering Company	8
19	Lindsey, Jonathan S.	North Carolina State University	8
20	Zare, Richard N.	Board of Trustees of the Leland Stanford Junior University	7
21	Lieber, Charles M.	President and Fellows of Harvard College	7

Table 7. Top PI-inventors with the largest number of NSF awards (1991–2002)

Rank	PI-inventors	Institution	Number of grants
1	Smith, Henry I.	Board of Supervisors of Louisiana State University and Agricultural	12
2	Lieber, Charles M.	President and Fellows of Harvard College	9
3	Safinya, Cyrus R.	The Regents of the University of California	9
4	Sellmyer, David J.	Board of Regents of the University of Nebraska	8
5	Bard, Allen J.	Board of Regents, The University of Texas System	8
6	Klabunde, Kenneth J.	Kansas State University Research Foundation	8
7	Dzenis, Yuris A.	Board of Regents, University of Nebraska-Lincoln	8
8	Requicha, Aristides A. G.	University of Southern California	7
9	Awschalom, David D.	The Regents of the University of California	7
10	Hansma, Paul K.	Digital Instruments, Inc.	7
11	Chou, Stephen Y.	Regents of the University of Minnesota	7
12	Lindsay, Stuart M.	Arizona Board of Regents acting on behalf of Arizona State University	7
13	Colvin, Vicki L.	The Regents of the University of California	7
14	Ruoff, Rodney S.	Washington University	6
15	Westervelt, Robert M.	President and Fellows at Harvard College	6
16	Hamilton, Andrew D.	University of Pittsburgh	6
17	Tour, James M.	University of South Carolina	6
18	Moore, Jeffrey S.	The Board of Trustees of the University of Illinois	6
19	Stucky, Galen D.	GRT, Inc.	6

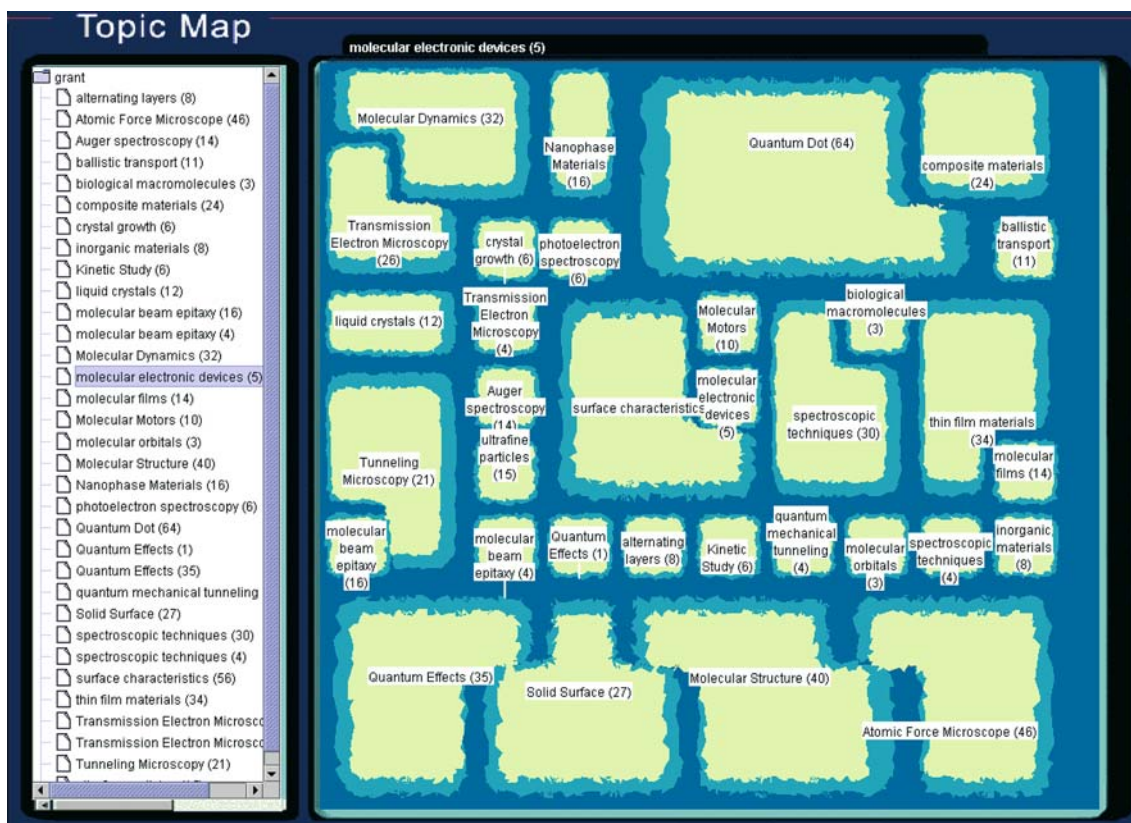


Figure 4. NSE-related award content map (1991–1995).

The top technology fields of the NSE-related patents are presented in Table 5. The first five fields are: “Chemistry: molecular biology and microbiology,” “Drug, bio-affecting and body treating compositions,” “Organic compounds – part of the class 532–570 series”, and “Semiconductor device manufacturing: process”.

By comparing the major NSF Divisions awards and the patent technology fields, we observe that the dominant positions of the NSF Divisions covering material science, chemistry, chemical engineering and device design and manufacturing are consistent with the importance of related technology areas reflected in the patent data. However, the major dominant fields related to biology and pharmaceutical research in NSE-related patents do not have a correspondent to major NSF Divisions. This difference may suggest that the NSF’s funding areas are different from other federal funding agencies such as the National Institutes of Health.

Trend analysis

Figure 1 shows that the growth of the number of NSE-related awards at NSF is similar to the growth of the number of NSE-related patents (full-text search by keywords) after 1991.

Four of the top five NSF Divisions, including the Division of Materials Research (DMR), Division of Chemistry (CHE), Division of Design, Manufacture and Industrial Innovation (DMI), and Division of Chemical and Transport Systems (CTS), had consistent prominent presence in NSE funding activities after 1994 (Figure 2). The DMR had a slight drop in funding activities in 2002, while the other three kept a general increasing trend. The Division of Electrical and Communications Systems (ECS) had substantial increases in NSE funding after 1998.

Figure 3 illustrates the patenting activity trends in the top 20 technology fields. The technology fields are listed in the order of decreasing total

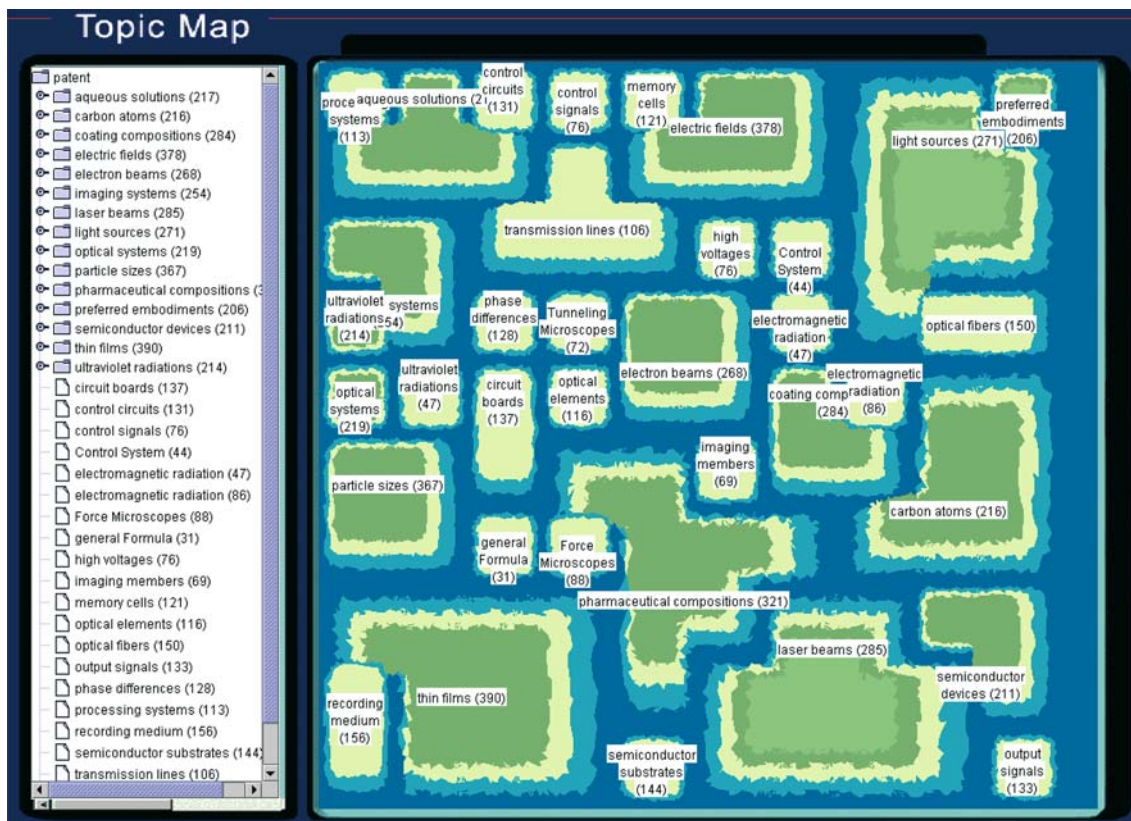


Figure 5. NSE-related patent content map (1991–1995).

number of patents issued between 1991 and 2002. The fastest growths in patenting activity in recent years are for “Chemistry: molecular biology and microbiology,” “Drug, bio-affecting and body treating compositions,” “Semiconductor device manufacturing: process,” and “Organic compounds – part of the class 532–570 series.”

Linking NSF award and patent data

The key linkage between the NSF awards and USPTO patents is the set of NSE-related patent inventors who are also principal investigators of NSE-related NSF awards. They are referred to as “*PI-inventors*” in this paper. We identified 307 *PI-inventors* by matching their names and their institutions in the award and patent datasets. These *PI-inventors* were associated with 760 *NSE-related patents* and 628 *NSF awards*.

Table 6 shows the top *PI-inventors* with the largest numbers of NSE-related patents. Thomas

J. Pinnavaia of Michigan State University (also Claytec, Inc.) topped the list with 30 patents, followed by George M. Whitesides of Harvard University (also with several companies), who had filed 24 NSE-related patents. The remaining top 6 *PI-inventors* measured by number of NSE-related patents were: Stuart M. Lindsay of Arizona State University (also Molecular Imaging Corporation), Mark E. Thompson of the University of Southern California, Sanford A. Asher of University of Pittsburgh, and Charles R. Cantor of Boston University (also Genelabs Technologies, Inc).

Table 7 lists the top *PI-inventors* in terms of number of NSE-related awards. Henry I. Smith from Louisiana State University and MIT topped the list with 12 NSE-related awards. The next six top *PI-inventors* are: Charles M. Lieber from Harvard, Cyrus R. Safinya from the University of California, David J. Sellmyer from the University of Nebraska, Allen J. Bard from the University of Texas, and Kenneth J. Klabunde from Kansas

State University. By comparing Tables 6 and 7, we observe that the top PI-inventors with the largest number of NSE-related patents do not appear to overlap with the top PI-inventors with the largest numbers of NSE-related awards. Only Allen J. Bard appeared near the top of both lists, 9th in Table 6 and 5th in Table 7. Matching the complete lists in Tables 6 and 7 we *identify only five PI-inventors as overlaps*, including Stuart M. Lindsay, Paul K. Hansma, Allen J. Bard (of the University of Texas), Kenneth J. Klabunde, and Charles M. Lieber. These findings would indicate that most PI-inventors either focus on fundamental research projects (as those funded by NSF) or commercial technology development. Only a small set of them was highly active in both arenas.

Content map analysis

Previous evaluation studies of R&D funding have been typically based on publication and citation counts. In this paper, we rely on advanced text analysis and visualization techniques (topic map) to comparatively evaluate the technology topics of the NSE-related awards and patents.

A topic map contains two components: a folder tree displayed on the left-hand side and a hierarchical content map on the right-hand side. The award/patent documents are organized under technology topics, which are represented as nodes in the folder tree and colored regions in the content map. These topics were labeled by representative noun phrases using a Natural Language Processing tool, the Arizona Noun Phraser, which identifies the key noun phrases based primarily on linguistic patterns (Tolle & Chen 2000). Numbers of patent documents that were assigned to the first-level topics are presented in the parentheses after the topic labels. The layers of the colored regions represent the levels of the hierarchies inside the specific regions.

The mapping is based on the multi-level self-organization map algorithm (Chen et al., 1996; Ong et al., 2004) developed by the Arizona Artificial Intelligence Lab. This algorithm takes as input titles and abstracts of documents and produces hierarchical groupings of these documents to form labeled topic regions organized in a content map. In each level of the topic map, conceptually closer technology topics were positioned closer

geographically. Conceptual closeness was derived from the concurrent patterns of key phrases in document titles and abstracts. The sizes of the topic regions also generally correspond to the number of documents assigned to the topics (Lin et al., 2000). We have successfully applied this content mapping tool previously for NSE-related patent analysis (Huang et al., 2003, 2004).

The award and patent content maps for three time intervals of 1991–1995, 1996–2000, and 2001–2002 are presented. For content maps of 1996–2000 and 2001–2002 (Figures 6–10) we visualize the changes of topic areas from the previous time period using different colors to indicate the growth rate of a topic area. 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 base growth rate was computed as the ratio between the total number of documents in the current time period and that of the previous time period. A topic region with similar growth rate as the base growth rate was assigned a green color that is consistent with the region color in the 1991–1995 content maps. The higher (or lower) the growth rate of a topic region is, the warmer (or colder) the color assigned.

We also analyzed the distribution of NSF Divisions and Directorates covering the topic areas in the award content map. For each topic region “*i*”, we counted the number of awards v_{ij} in each Division/Directorate “*j*”. We present the dominant NSF Divisions/Directorates for each topic region in a table. Divisions/Directorates of a topic region that had more than $\mu_i + \sigma_i$ awards were considered dominant Divisions/Directorates, where μ_i and σ_i are the average and standard deviation of v_{ij} .

Content map analysis for 1991–1995

Figures 4 and 5 illustrate NSE-related award and patent content maps from 1991 to 1995, respectively. Figure 4 shows that from 1991 to 1995, the NSE-related NSF awards were concentrated in several technology topics including “Quantum Dot,” “surface characteristics,” “Atomic Force Microscope,” and “Molecular Structure.”

Figure 5 shows NSE-related patents cover broader technology topics including “light sources,” “carbon atoms,” “pharmaceutical compositions,” “thin films,” and “laser beams.” The topic

Table 8. NSF division/directorate distribution of awards per topic area (1991–1995)

Region size	Region label	Number of awards	Average amount	Major division	Major directorate
13	Quantum Dot	64	209,000	DMR(30)	MPS(37)
9	Molecular Structure	40	233,000	DUE(12); CHE(8)	MPS(15)
8	Quantum Effects	36	817,000	DMR(16)	MPS(26)
7	Surface Characteristics	56	456,000	CHE(19); DMR(16)	MPS(35)
7	Atomic Force Microscope	46	160,000	DMR(17)	MPS(20)
7	Solid Surface	27	201,000	CHE(7)	ENG(13)
6	Spectroscopic Techniques	34	514,000	DMR(11)	MPS(15)
5	Thin Film Materials	34	239,000	CHE(7); CTS(6)	MPS(12); ENG(9)
5	Molecular Dynamics	32	262,000	DMR(9); CHE(8)	MPS(18)
5	Tunneling Microscopy	21	219,000	DMR(7); CHE(6)	MPS(13)
4	Transmission Electron Microscopy	30	234,000	DMR(13); CHE(11)	MPS(24)
4	Composite Materials	24	400,000	DMR(11)	MPS(11)
2	Molecular Beam Epitaxy	20	364,000	DMR(10)	MPS(11)
2	Nanophase Materials	16	177,000	DMR(6)	MPS(6); ENG(5)
2	Liquid Crystals	12	2,034,000	DMR(8)	MPS(10)
1	Ultrafine Particles	15	190,000	DMR(5)	MPS(7)
1	Auger Spectroscopy	14	408,000	DMR(7)	MPS(9)
1	Molecular Films	14	347,000	CHE(4)	MPS(7)
1	Ballistic Transport	11	223,000	DMR(8)	MPS(8)
1	Molecular Motors	10	125,000	MCB(6)	BIO(6)
1	Alternating Layers	8	202,000	DMR(4)	MPS(6)
1	Inorganic Materials	8	172,000	CHE(3); DMR(3)	MPS(6)
1	Crystal Growth	6	301,000	DMR(5)	MPS(5)
1	Kinetic Study	6	297,000	DMR(2); CHE(2); DUE(2)	MPS(4)
1	Photoelectron Spectroscopy	6	271,000	DMR(4)	MPS(4)
1	Molecular Electronic Devices	5	350,000	CHE(3)	MPS(3)
1	Quantum Mechanical Tunneling	4	423,000	ECS(2)	ENG(2)
1	Biological Macromolecules	3	76,000	MCB(1); DBI(1); CTS(1)	BIO(2)
1	Molecular Orbitals	3	148,000	DUE(2)	EHR(2)

labels are noun phrases extracted using the Arizona Noun Phraser as described previously. These noun phrases were extracted from the original text and the capitalization varies. However, phrases with capitalization as well as morphological and inflectional variations were treated as the same phrase for the patent/award content representation used by the self-organizing map algorithm.

Table 8 summarizes the distribution of awards per NSF Divisions and Directorates between 1991 and 1995. The numbers in the parentheses after the dominant Divisions/Directorates indicate the number of awards under that Division/Directorate within the topic region. “Quantum Dot” was the largest region in the NSE-related award content map for this time period. Sixty-four awards were grouped into this area with an

average funding amount of \$209,000. The Division of Materials Research (DMR) has a large contribution with 30 out of 64 awards of the region. The Directorate for Mathematical and Physical Sciences (MPS) was the most active Directorate of the region with 37 out of 64 awards. Most other topic areas, such as “Quantum Effects,” “Atomic Force Microscope,” and “spectroscopic techniques” were similarly dominated by the DMR and MPS. There were 10 topic areas that had multiple dominant Divisions. For example, “Molecular Structure” had 12 awards under the Division of Undergraduate Education (DUE) and 8 awards under the Division of Chemistry (CHE). Overall, DMR under MPS dominated the majority of topic areas of the NSE-related awards from 1991 to 1995.

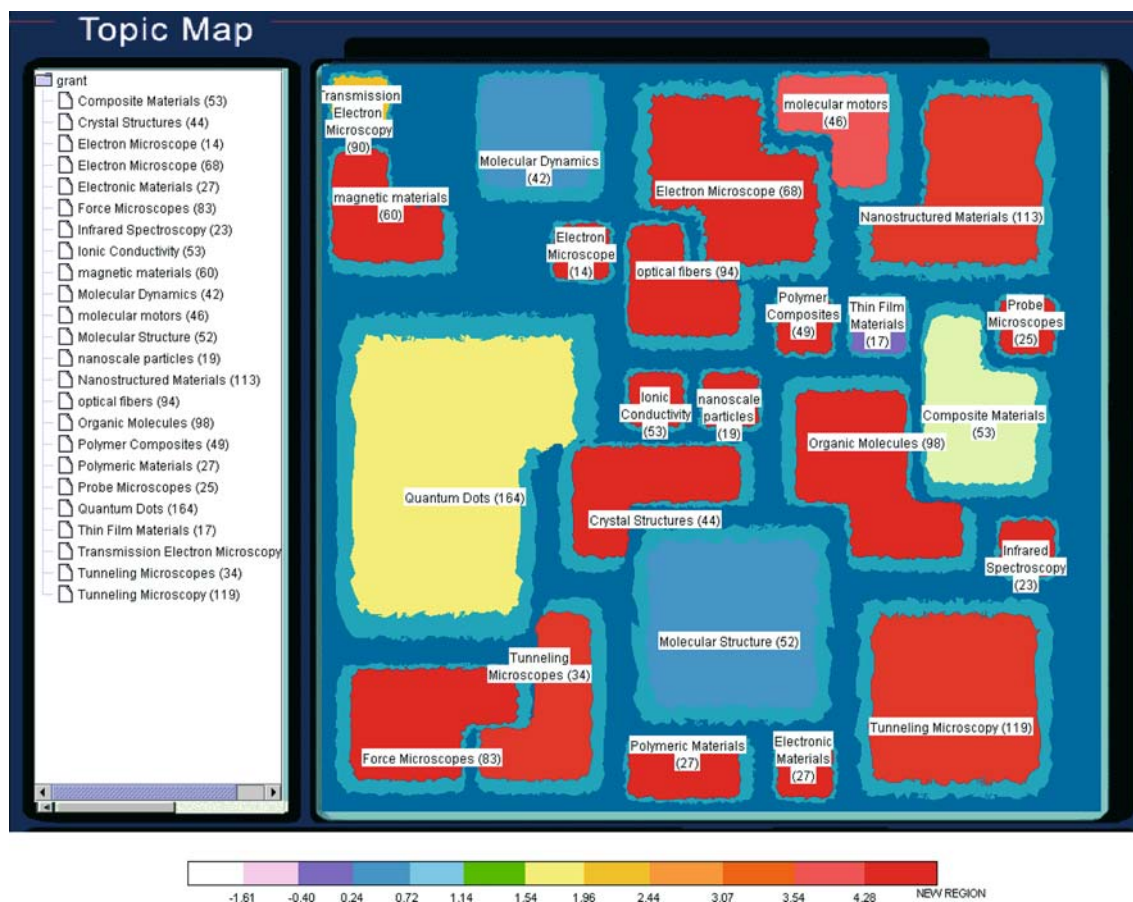


Figure 6. NSE-related award content map (1996–2000): The color scale shows the growth rate of the number of awards in the respective topic.

Content map analysis for 1996–2000

Figure 6 presents the award content map for the interval 1996–2000. It displays many new award topics (shown as red regions), for instance, “Organic Molecules,” “Electron Microscope,” “optical fibers,” “polymeric materials,” and “crystal structures.” The major topic areas of “Tunneling Microscopy,” “Nanostructured Materials” (shown as red regions because of large growth rates) and “Transmission Electron Microscopy” and “Quantum Dots” (shown as orange and yellow regions) continue with a higher growth rate than the base rate. The topic area “Composite Materials” (shown as green regions) had the base growth rate. Other topic areas, including “Molecular Structure,” “Molecular Dynamics” and “Thin Film Materials” (shown as

blue and purple regions), had a lower growth rate than the base growth rate. In general, the microscope-related topics continue to dominate NSE-related NSF awards. The detailed topic region growth rates and base growth rate are also presented in Table 9.

Table 10 presents the major Division/Directorate contributing to various topic areas during 1996–2000. The DMR Division under MPS Directorate was still the dominant source of funding. CHE started to be another important Division after MPS. The Engineering (ENG) Directorate also funded a significant number of awards in many small award topic areas. A significant difference from the previous time period is that more than half of the topic areas now had multiple funding Divisions, indicating more diversified funding sources for NSE-related

Table 9. NSE-related award change details (1996–2000)

Region label	# of Awards in the region (1996–2000)	# of Awards in the region (1991–1995)	Growth rate
Crystal Structures	44	0	N/A
Electron Microscope	82	0	N/A
Electronic Materials	27	0	N/A
Force Microscopes	83	0	N/A
Infrared Spectroscopy	23	0	N/A
Ionic Conductivity	53	0	N/A
Magnetic Materials	60	0	N/A
Nanoscale Particles	19	0	N/A
Optical Fibers	94	0	N/A
Organic Molecules	98	0	N/A
Polymer Composites	49	0	N/A
Polymeric Materials	27	0	N/A
Probe Microscopes	25	0	N/A
Tunneling Microscopes	153	21	6.29
Nanostructured Materials	113	16	6.06
Molecular Motors	46	10	3.60
Transmission Electron Microscopy	90	26	2.46
Quantum Dots	164	64	1.56
Composite Materials	53	24	1.21
Molecular Dynamics	42	32	0.31
Molecular Structure	52	40	0.30
Thin Film Materials	17	34	-0.50
Baseline Growth Rate			1.337

Table 10. NSF division/directorate of awards per topic area (1996–2000)

Region size	Region label	Number of awards	Average amount	Major division	Major directorate
17	Quantum Dots	164	238,000	DMR(85)	MPS(99)
9	Tunneling Microscopy	119	449,000	DMR(64)	MPS(88)
9	Molecular Structure	52	500,000	DMR(14); CHE(7)	MPS(23)
8	Electron Microscope	82	322,000	DMR(35)	MPS(42); ENG(32)
7	Nanostructured Materials	113	953,000	DMR(50)	MPS(58)
6	Organic Molecules	98	323,000	CHE(26); CTS(23); DMR(22)	MPS(48)
5	Force Microscopes	83	229,000	DMR(24); CTS(15)	ENG(34); MPS(27)
5	Composite Materials	53	248,000	DMR(17); DMI(11)	ENG(27)
4	Crystal Structures	44	251,000	DMR(15); CHE(15)	MPS(30)
4	Molecular Dynamics	42	276,000	DMR(8); CHE(8); ACI(6)	MPS(19)
4	Tunneling Microscopes	34	246,000	DMR(23)	MPS(26)
3	Optical Fibers	94	255,000	DMR(27)	MPS(41); ENG(36)
3	Magnetic Materials	60	395,000	DMR(31)	MPS(43)
3	Molecular Motors	46	253,000	MCB(14)	BIO(19)
2	Transmission Electron Microscopy	90	295,000	DMR(38)	MPS(62)
2	Polymeric Materials	27	1,164,000	DMR(20)	MPS(23)
1	Ionic Conductivity	53	261,000	DMR(14); CTS(11); CHE(10)	MPS(24); ENG(22)
1	Polymer Composites	49	273,000	DMI(8); CHE(8); DMR(7)	ENG(22)
1	Electronic Materials	27	326,000	DMR(13)	MPS(22)
1	Probe Microscopes	25	280,000	DMR(7); DUE(4)	MPS(9)
1	Infrared Spectroscopy	23	205,000	CHE(7); DMR(7)	MPS(14)
1	Nanoscale Particles	19	184,000	DMR(5)	MPS(9)
1	Thin Film Materials	17	1,634,000	CHE(4); DMI(4)	ENG(8); MPS(8)

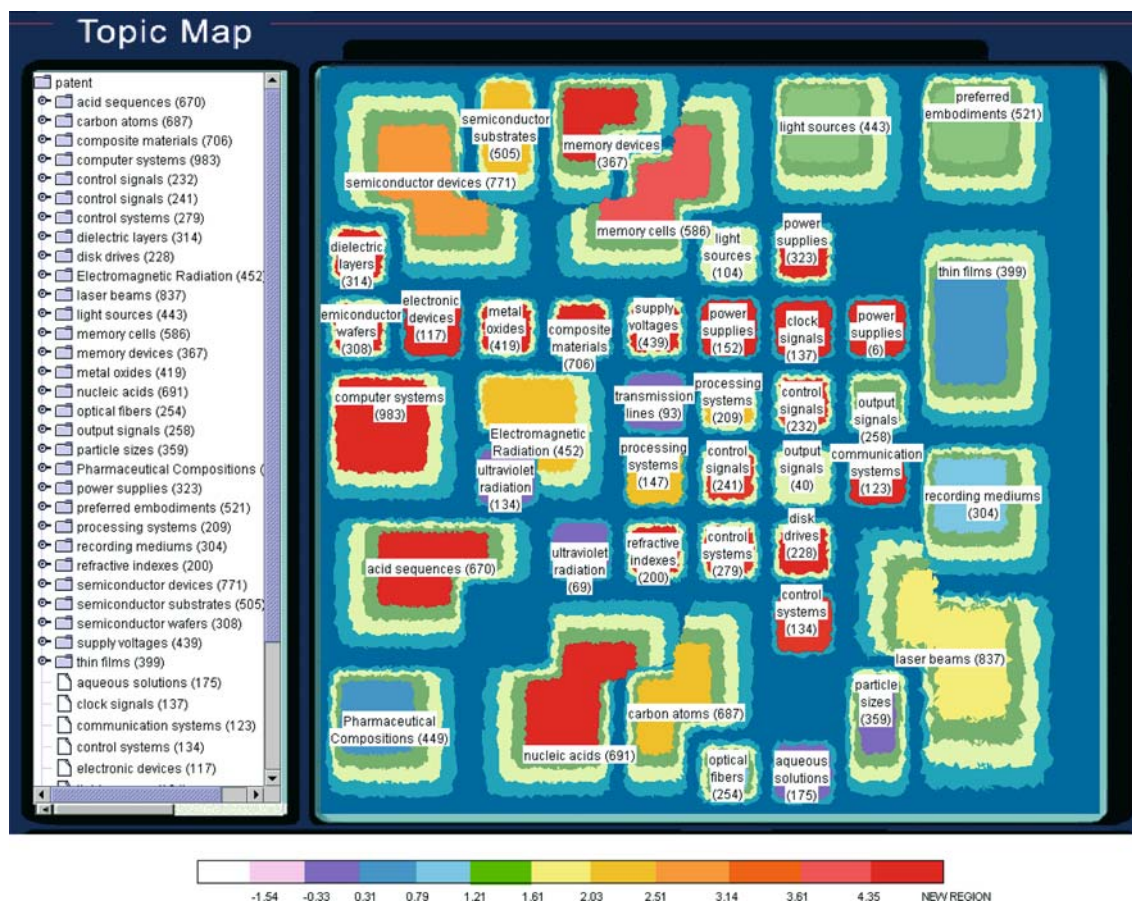


Figure 7. NSE-related patent content map (1996–2000). The color scale shows the growth rate of the number of patents in the respective topic.

projects and increasing the role of engineering (ENG).

Figure 7 presents the patent content map of the same time period. The dominant patent topics were “semiconductor devices,” “memory cells,” “thin films,” “acid sequences,” “nucleic acids,” and “laser beams.” Newly appeared topic areas include “memory devices,” “dielectric layers,” “semiconductor wafers,” “electronic devices,” “metal oxides,” “composite materials,” “supply voltages,” “power supplies,” “clock signals,” “computer systems,” “communication systems,” “acid sequence,” “refractive indexes,” “nucleic acids,” and “disk drives.” Table 11 presents the detailed growth rate information. Similar to the topic areas in the award content map, most patent topic areas were new or had a higher growth rate than the base rate, indicating that the patents

issued in 1996–2000 were dominated by new topic areas.

Content map analysis for 2001–2002

Figure 8 presents the award content map for 2001–2002, with the growth rates per topic area presented in Table 12. We observe that award topics continued to focus on microscopy-, molecular- and quantum-related topics. New topics include “Quantum Effects,” “Molecular Modeling,” “Scanning Probe Microscopy,” “Organic Materials,” “Nanoscale Materials,” “Polymer Blends,” “quantum computers,” “thermal stabilities,” “artificial biomimetic,” “Quantum Information Processing,” and “femtosecond laser.” Some of these new topic region labels were variations of or closely related to topic areas in previous

Table 11. Growth rates for NSE-related patents (1996–2000)

Region label	# of Patents in the region (1996–2000)	# of Patents in the region (1991–1995)	Growth rate
Acid Sequences	670	0	N/A
Clock Signals	137	0	N/A
Communication Systems	123	0	N/A
Composite Materials	706	0	N/A
Computer Systems	983	0	N/A
Dielectric Layers	314	0	N/A
Disk Drives	228	0	N/A
Electronic Devices	117	0	N/A
memory devices	367	0	N/A
Metal Oxides	419	0	N/A
Nucleic Acids	691	0	N/A
Power Supplies	481	0	N/A
Refractive Indexes	200	0	N/A
Semiconductor Wafers	308	0	N/A
Supply Voltages	439	0	N/A
Control Systems	413	44	8.39
Control Signals	473	76	5.22
Memory Cells	586	121	3.84
Semiconductor Devices	771	211	2.65
Semiconductor Substrates	505	144	2.51
Electromagnetic Radiation	452	133	2.40
Carbon Atoms	687	216	2.18
Processing Systems	356	113	2.15
Laser Beams	837	285	1.94
Preferred Embodiments	521	206	1.53
Output Signals	298	133	1.24
Light Sources	547	271	1.02
Recording Mediums	304	156	0.95
Optical Fibers	254	150	0.69
Pharmaceutical	449	321	0.40
Compositions			
Thin Films	399	390	0.02
Particle Sizes	359	367	-0.02
Transmission Lines	93	106	-0.12
Aqueous Solutions	175	217	-0.19
Ultraviolet Radiation	203	261	-0.22
Baseline Growth Rate			1.408

time periods, such as “Molecular Modeling,” “Organic Materials,” and “Polymer Blends.” Several of these new topic areas turned out to truly represent new directions in the field, such as “quantum computers,” “artificial biomimetic,” and “femtosecond laser.”

Table 13 presents the major Division/Directorate per topic area in 2001–2002. Continuing the trend from 1996–2000, the Engineering Directorate had a more prominent presence in most major topic areas and become an important funding source for NSE research comparable to the MPS Directorate. At the same time, the DMR Division still dominated most topic areas, but many other

dominant funding Divisions contributed significantly as well, including CTS, DMI, CHE, MCB, CMS, and ECS.

The most important patent topics continued to be “thin films,” “preferred embodiments,” “nucleic acids,” “pharmaceutical compositions,” “laser beams,” and “semiconductor devices” during 2001–2002 (Figure 9). The detailed topic area changes are presented in Table 14. Compared to the previous time period, there were fewer new topic areas during 2001–2002. These include “functional groups,” “(such) polypeptides,” “electric fields,” “optical systems,” “reaction products,” “optical signals,” “substrate

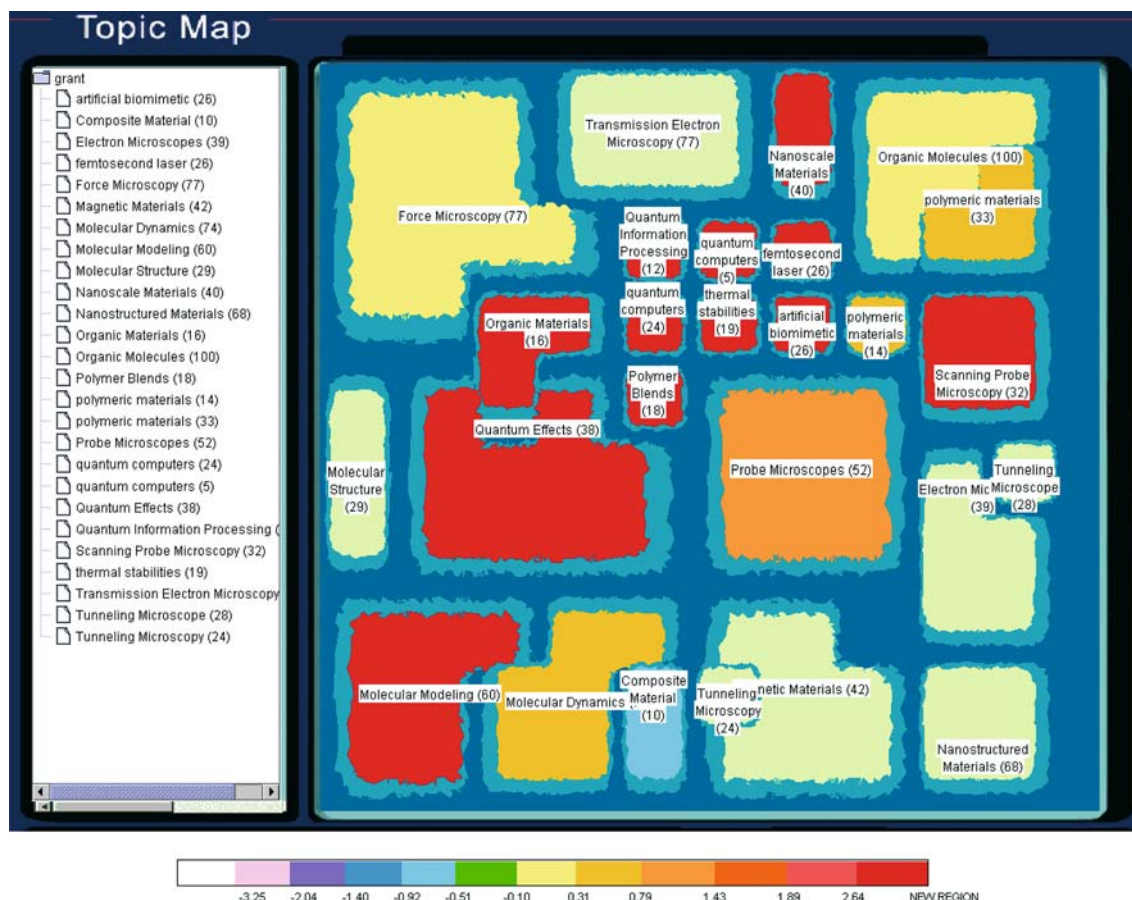


Figure 8. NSE-related award content map (2001–2002).

surfaces,” “dielectric materials,” and “silicon substrates.”

For both the award and patent topic maps, the numbers of new topics were smaller in 2001–2002 than in 1996–2000. This is mainly because the content maps are only for a two-year interval as compared to the previous interval of five-years (1996–2000). The annual rate of change increased in 2001–2002 as compared to the previous interval.

Award/patent map topic associations

We visualize the award-patent links per topic for of all three time periods using a “topic association network” (Figure 10). Here, the award and patent topics identified in the content maps are

shown as circles and triangles, respectively. The green, orange, and red colors represent the three time periods, 1991–1995, 1996–2000, and 2001–2002, respectively. Links were allowed only between award and patent topics to indicate associations between an award topic and its related patent topics. These links were created by consulting a nanotechnology expert. We generated two lists of award and patent topics that appeared in the content maps. The expert was asked to identify the relevant patent topics for each award topic. In Figure 10 we placed nodes that represent the same topics in different time periods close to each other. For example, the patent topic “electromagnetic radiation” in the upper-right corner of Figure 10 appeared in the patent content maps of all three time periods.

Table 12. Growth rate of NSE-related award per detailed topic areas in 2001–2002 as compared to 1996–2000

Region label	# of Awards in the region (2001–2002)	# of Awards in the region (1996–2000)	Growth rate
Artificial Biomimetic	26	0	N/A
Femtosecond Laser	26	0	N/A
Molecular Modeling	60	0	N/A
Nanoscale Materials	40	0	N/A
Organic Materials	16	0	N/A
Polymer Blends	18	0	N/A
Quantum Computers	29	0	N/A
Quantum Effects	38	0	N/A
Quantum Information Processing	12	0	N/A
Scanning Probe Microscopy	32	0	N/A
Thermal Stabilities	19	0	N/A
Probe Microscopes	52	25	1.08
Molecular Dynamics	74	42	0.76
Polymeric materials	47	27	0.74
Organic Molecules	100	98	0.02
Force Microscopy	77	83	-0.07
Transmission Electron Microscopy	77	90	-0.14
Magnetic Materials	42	60	-0.30
Nanostructured Materials	68	113	-0.40
Molecular Structure	29	52	-0.44
Electron Microscopes	39	82	-0.52
Tunneling Microscopy	52	153	-0.66
Composite Material	10	53	-0.81
Baseline Growth Rate			-0.305

They associated with the award topic “Infrared Spectroscopy” in 1996–2000.

Figure 10 shows that most NSE-related award topics are relevant to NSE-related patent topics. A large connected component award/patent map consists of material- and optics-related topics. There are also several isolated topic areas, which are circled with red dotted lines in the figure. The two most important isolated topic association clusters were in the lower-right part of Figure 10, corresponding to topics related to organic molecular and composite materials. Several dense topic association clusters (marked using circles of blue dotted lines) also appear in the large connected component. These may represent the central topic areas of NSF-funded NSE research and their impacted patent areas. Most topics in these clusters are optics and material topics.

We observe several local award/patent topic association patterns (Figure 10):

- Pattern I (marked with red squares): *An award topic followed by several associated patent topics in later time periods.* This pattern may indicate

that a new research funded by the NSF eventually invoked substantial industry efforts. Such award topics include “molecular electronic devices,” “Transmission Electron Microscopy,” “inorganic materials,” “molecular beam epitaxy,” and “spectroscopic techniques.”

- Pattern II (marked with orange circles): *Consistent award and patent topic associations throughout all time periods.* This pattern may indicate that basic research and industry development evolve in parallel in these areas. Such award topics include “quantum dots,” “probe microscopes,” “nanostructured materials,” and “magnetic materials.”
- Pattern III (marked with blue round squares): *A patent topic followed by award topics in the later time periods.* Such patterns may indicate that basic research was initiated by early industry developments in related areas. Such award topics include “nanoscale particles,” “infrared spectroscopy,” “femtosecond laser,” “optical fibers,” “crystal structures,” and “Scanning Probe Microscopy.”

Table 13. Major NSF division/directorate per topic area (2001–2002)

Region size	Region label	Number of awards	Average amount	Major division	Major directorate
12	Force Microscopy	77	421,000	MPS(27); ENG(27)	DMR(23); CTS(11)
10	Quantum Effects	38	360,000	MPS(26)	DMR(14)
9	Probe Microscopes	52	1,021,000	ENG(28)	DMR(16); DMI(10)
7	Molecular Modeling	60	426,000	ENG(16); MPS(15)	CTS(11); CHE(10); MCB(7)
7	Magnetic Materials	42	810,000	MPS(28)	DMR(20)
6	Organic Molecules	100	511,000	MPS(46); ENG(40)	DMR(29); ECS(17); CHE(14)
6	Transmission Electron Microscopy	77	411,000	MPS(48)	DMR(33)
6	Molecular Dynamics	74	549,000	ENG(40)	DMR(16); CTS(14); DMI(10); CMS(9)
5	Nanostructured Materials	68	1,310,000	ENG(31); MPS(28)	DMR(23)
5	Electron Microscopes	39	433,000	MPS(18); ENG(17)	DMR(17)
4	Polymeric Materials	47	547,000	MPS(23)	DMR(17)
4	Scanning Probe Microscopy	32	422,000	MPS(23)	DMR(13); CHE(9)
3	Molecular Structure	29	1,036,000	MPS(16)	CHE(9); DMR(7)
3	Organic Materials	16	230,000	ENG(6)	ECS(3); CHE(3); OCE(3); DMR(2)
2	Nanoscale Materials	40	771,000	MPS(15); ENG(12)	DMR(11); ECS(9)
2	Quantum Computers	29	625,000	MPS(13)	DMR(7); ECS(6)
2	Composite Material	10	333,000	ENG(6)	ECS(3); CTS(2); DMR(2)
1	Tunneling Microscope	28	909,000	MPS(21)	DMR(19)
1	Artificial Biomimetic	26	477,000	MPS(19)	CHE(9); DMR(9)
1	Femtosecond Laser	26	401,000	ENG(17)	DMI(7); DMR(5)
1	Tunneling Microscopy	24	360,000	MPS(12)	DMR(7)
1	Thermal Stabilities	19	258,000	ENG(11)	DMI(6)
1	Polymer Blends	18	214,000	MPS(13)	DMR(10)
1	Quantum Information Processing	12	457,000	MPS(6); ENG(6)	DMR(4); ECS(4)

Critical patent/inventor analysis

An analysis of patents and inventors that have the highest impact in NSE research and development is presented based on patent citation. We refer to these patents and inventors in different subfields as “critical patents/inventors.” In this section, the NSE-related patent data during 1976–1990 are added in analysis for a more comprehensive assessment. Details regarding the complete NSE-related patent dataset can be found in previous work (Huang et al., 2003, 2004).

Measures

A simple measure of the impact used in bibliometric and patent analysis is the number of times

an author, paper or patent is cited by others. The *citation count* was initially introduced for evaluating academic publications. 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. This idea is supported by a substantial amount of academic literature on citation indexing. Garfield’s 1955 vision of an interdisciplinary science citation index introduced the concept of citation as an impact factor indicator and the concept has since been widely applied, for example, in the ResearchIndex’s citation context tool (Lawrence et al., 1999).

Based on a similar idea, the citations among patents also indicate the authority of patents and

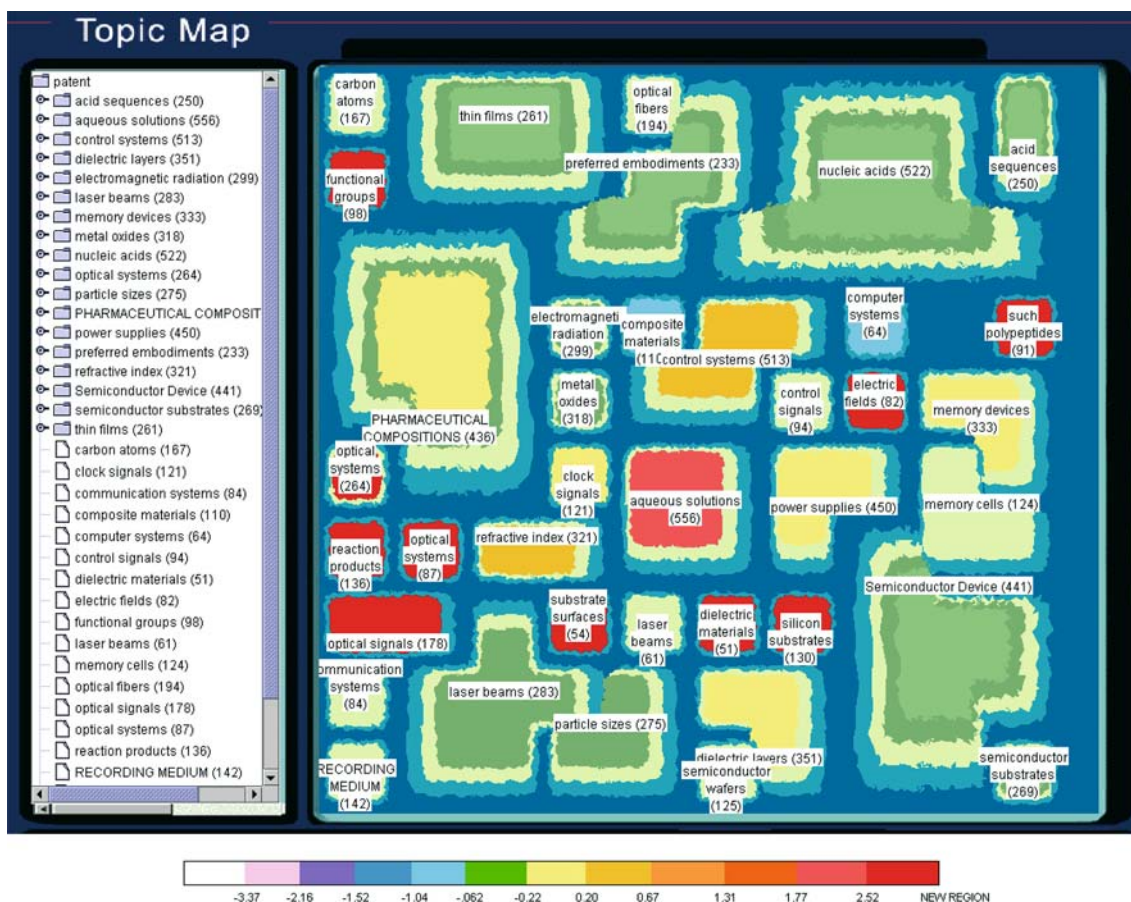


Figure 9. NSE-related patent content map (2001–2002).

inventors in a technology field. Patent documents are required by law to cite all important prior arts 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, patent citation analysis has been widely applied in practical technology analysis of various domains (e.g., Narin, 2000; Huang et al., 2003). The number of citations received by a patent has been the main measure in evaluating impact and quality of patents, inventors, and the technology competence of institutions and countries. In our study, we define a *number of cites measure for a patent* as the number of later patents from which this patent receives citations and a *number of cites measure for an inventor* as the sum of the number of cites of all his/her patents.

In addition of using this simple measure of number of cites, we also assign inventors and patents an *Authority Score* based on the Hypertext Induced Topic Selection (HITS) algorithm (Kleinberg, 1998), which was intended for identifying important web pages based on hyperlink citation structure. Following the formulation of the original HITS algorithm, two types of scores are defined for each patent, an Authority Score and a Hub Score. A patent with a high Authority Score has a significant impact/influence on the follow-up patents, meaning the technology described by the patent has become the foundation of many later technologies. A high Hub Score, on the other hand, indicates that a patent has cited many critical patents and describes a new technology that integrates many important prior innovations. The Authority and Hub Scores mutually reinforce each other. With a patent citation dataset, we initialize the Authority Scores as the

Table 14. Growth rate of NSE-related patent per detailed topic area in 2001–2002 as compared to 1996–2000

Region label	# of Patents in the region (2001–2002)	# of Patents in the region (1996–2000)	Growth rate
Dielectric Materials	51	0	N/A
Electric Fields	82	0	N/A
Functional Groups	98	0	N/A
Optical Signals	178	0	N/A
Optical Systems	351	0	N/A
Reaction Products	136	0	N/A
Silicon Substrates	130	0	N/A
Substrate Surfaces	54	0	N/A
Such Polypeptides	91	0	N/A
Aqueous Solutions	556	175	2.18
Refractive Index	321	200	0.61
Control Systems	513	413	0.24
Dielectric Layers	351	314	0.12
Pharmaceutical CI	436	449	-0.03
Power Supplies	450	481	-0.06
Memory Devices	333	367	-0.09
Clock Signals	121	137	-0.12
Particle Sizes	275	359	-0.23
Optical Fibers	194	254	-0.24
Metal Oxides	318	419	-0.24
Nucleic Acids	522	691	-0.24
Communication Systems	84	123	-0.32
Electromagnetic Radiation	299	452	-0.34
Thin Films	261	399	-0.35
Semiconductor Device	441	771	-0.43
Semiconductor Substrates	269	505	-0.47
Recording Medium	142	304	-0.53
Preferred Embodiments	233	521	-0.55
Laser Beams	344	837	-0.59
Semiconductor Wafers	125	308	-0.59
Acid Sequences	250	670	-0.63
Carbon Atoms	167	687	-0.76
Memory Cells	124	586	-0.79
Control Signals	94	473	-0.80
Composite Materials	110	706	-0.84
Computer Systems	64	983	-0.93
Baseline Growth Rate			-0.424

number of times the patents are cited by others and the Hub Scores as the number of times the patents cite others. The two scores are then computed following an iterative updating procedure:

$$\begin{aligned}
 \text{Authority Score}(p) &= \sum_{q \text{ has cited } p} \text{Hub Score}(q) \\
 \text{Hub Score}(q) &= \sum_{p \text{ has cited } q} \text{Authority Score}(p)
 \end{aligned}
 \tag{1}$$

The Authority Score we use for our study is obtained with three iterations of score updating. It essentially incorporates the number of citations

received by a patent, the patents citing it, and patents citing those citing patents. The simple number of cites measure can be viewed as a local measure of impact, while the Authority Score provides a global impact measure that accounts for transitive citations. Based on the Authority Score of patents, we similarly define the Authority Score of an inventor as the sum of the Authority Scores of his/her patents.

Subfield analysis

We have identified the highest ranked PI-inventors and PI-inventors' patents based on both the

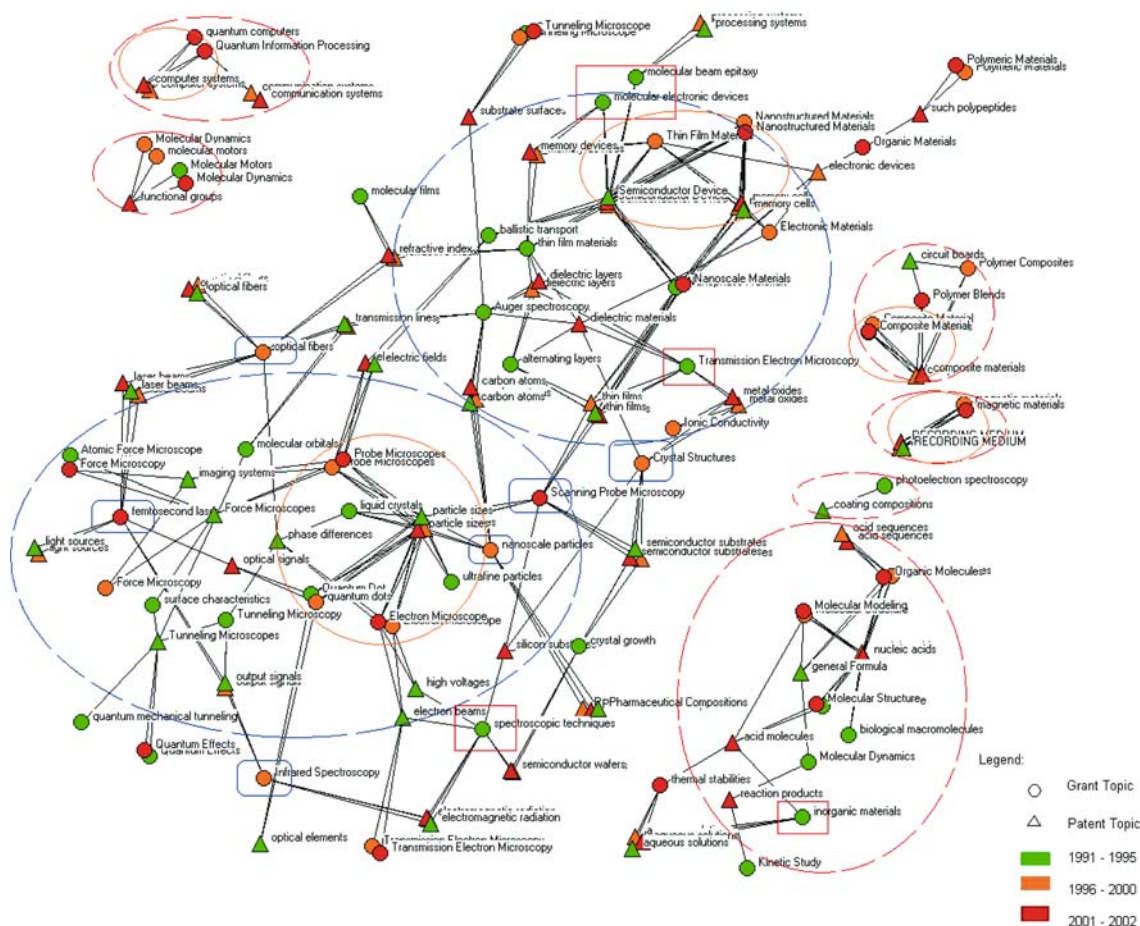


Figure 10. NSE-related award/patent topic associations¹: longitudinal links for 1991–1995, 1996–2000 and 2001–2002.

number of cites and Authority Score in NSE subfields. For each subfield, the scores of a PI-inventor are derived by summing the scores of the patents of a PI-inventor in that subfield.

The top 20 NSE fields from 1976 to 2003 have been analyzed. Table 15 presents the PI-inventors' patents that received the highest number of cites per subfield. For 10 of these subfields – the top PI-inventor patents ranks above 20. Considering the much smaller size of the pool of PI-inventors (307) relative to the entire set of NSE-related patent inventors (123,752), the rankings of PI-inventors shows their significant impact on NSE development.

The highest ranked PI-inventor patents are: (1) “Formation of microstamped patterns on surfaces and derivative articles” (patent number 5512131) filed by the University of California, which

received 40 citations and was ranked 4th in the subfield of “Semiconductor device manufacturing: process;” (2) “Atomic force microscope with optional replaceable fluid cell” (patent number 4935634) filed by Columbia University, which received 58 citations and was ranked 5th in the subfield “Radiant energy.”

The highest rank of PI-inventor patents in the second largest NSE subfield “Drug, bio-affecting and body treating compositions” was only 268th. Other subfields in which PI-inventors' patents had low rankings were: “Optics: systems (including communication) and elements” (the highest rank of PI-inventor patent is the 72nd) and “Coating processes” (the highest rank of PI-inventor is also the 72nd). These fields represent technology areas where NSF-funded research had substantially lower impact.

Table 15. Critical patent analysis: number of cites

Rank	US patent classification	Name	Number of patents	Highest ranked PI-inventor patent measured by Number of cites
1	435	Chemistry: molecular biology and microbiology	7946	29th: [5620850] "Molecular recognition at surfaces derivatized with self-assembled monolayers." President and Fellows of Harvard College. NumCites = 41
2	514	Drug, bio-affecting and body treating compositions	6183	268th: [5157032] "Mixed ligand complexes and uses thereof as binding agents and probes to DNA." The Trustees of Columbia University in the City of New York. NumCites = 6
3	424	Drug, bio-affecting and body treating compositions	4683	53rd: [4721669] "Chemical probes for left-handed DNA and chiral metal complexes as Z-specific anti-tumor agents." The Trustees of Columbia University in the City of New York. NumCites = 23
4	250	Radiant energy	4657	5th: [4935634] "Atomic force microscope with optional replaceable fluid cell." The Regents of the University of California. NumCites = 58
5	428	Stock material or miscellaneous articles	3939	16th: [4728591] "Self-assembled nanometer lithographic masks and templates and method for parallel fabrication of nanometer scale multi-device structures." Trustees of Boston University. NumCites = 43
6	257	Active solid-state devices (e.g., transistors, solid-state diodes)	3933	30th: [5751018] "Semiconductor nanocrystals covalently bound to solid inorganic surfaces using self-assembled monolayers." The Regents of the University of California. NumCites = 20
7	438	Semiconductor device manufacturing: process	3877	4th: [5512131] "Formation of microstamped patterns on surfaces and derivative articles." President and Fellows of Harvard College. NumCites = 40
8	536	Organic compounds – part of the class 532–570 series	3756	13th: [4500707] "Nucleosides useful in the preparation of polynucleotides." University Patents, Inc. NumCites = 35
9	530	Chemistry: natural resins or derivatives; peptides or proteins; lignins or reaction products thereof	3753	10th: [5620850] "Molecular recognition at surfaces derivatized with self-assembled monolayers." President and Fellows of Harvard College. NumCites = 41
10	359	Optics: systems (including communication) and elements	3404	72nd: [4187336] "Non-iridescent glass structures". NumCites = 14 72nd: [5036220] "Nonlinear optical radiation generator and method of controlling regions of ferroelectric polarization domains in solid state bodies."
11	427	Coating processes	3265	Leland Stanford Junior University. NumCites = 14 18th: [5512131] "Formation of microstamped patterns on surfaces and derivative articles." President and Fellows of Harvard College. NumCites = 40
12	436	Chemistry: analytical and immunological testing	3027	24th: [5472881] "Thiol labeling of DNA for attachment to gold surfaces." University of Utah Research Foundation. NumCites = 34
13	430	Radiation imagery chemistry: process, composition, or product thereof	2983	15th: [4728591] "Self-assembled nanometer lithographic masks and templates and method for parallel fabrication of nanometer scale multi-device structures." Trustees of Boston University. NumCites = 43

Table 15. (Continued)

14	356	Optics: measuring and testing	2957	25th: [4675300] "Laser-excitation fluorescence detection electrokinetic separation." The Board of Trustees of the Leland Stanford Junior University. NumCites = 24
15	365	Static information storage and retrieval	2310	48th: [5268862] "Three-dimensional optical memory." The Regents of the University of California. NumCites = 15
16	327	Miscellaneous active electrical nonlinear devices, circuits, and systems	2286	42nd: [5475341] "Sub-nanoscale electronic systems and devices." Yale University. NumCites = 9
17	204	Chemistry: electrical and wave energy	1864	20th: [5202004] "Scanning electrochemical microscopy." Digital Instruments, Inc. NumCites = 25
18	422	Chemical apparatus and process disinfecting, deodorizing, preserving, or sterilizing	1829	12th: [5620850] "Molecular recognition at surfaces derivatized with self-assembled monolayers." President and Fellows of Harvard College. NumCites = 41
19	372	Coherent light generators	1775	13th: [5036220] "Nonlinear optical radiation generator and method of controlling regions of ferroelectric polarization domains in solid state bodies." Leland Stanford Junior University. NumCites = 14
20	252	Compositions	1680	100th: [5324457] "Devices and methods for generating electrogenerated chemiluminescence." Board of Regents, The University of TX System. NumCites = 6

Table 16 presents the PI-inventors' patents that received the highest Authority Scores in the top 20 NSE subfields. In 12 of these subfields top PI-inventor patents have rankings above 20. The highest ranked PI-inventor patents are different from the ones ranked by number of cites in Table 15. These patents include: (1) "Self-assembled nanometer lithographic masks and templates and method for parallel fabrication of nanometer scale multi-device structures" (patent number 4728591) filed by Boston University, which was ranked 1st in the both the field "Stock material or miscellaneous articles" and the field "Radiation imagery chemistry: process, composition, or product thereof;" (2) "Scanning electrochemical microscopy" (patent number 5202004) filed by Digital Instruments (Allen J. Bard of the University of Texas), which was ranked 1st in the field "Chemistry: electrical and wave technology." Patent 4935634 by Columbia University was still highly ranked by the Authority Score; it was ranked 4th in the field "Radiant energy" (higher than its ranking by number of cites). However, patent 5512131 by the University of California was ranked much lower by the Authority Score than by number of cites. In the field "Semiconductor device manufacturing: process" the highest ranked PI-inventor patent by the Authority Score was filed by Stanford University and was ranked 9th.

Patents of PI-inventors had relatively low rankings in the following fields: "Drug, bio-affecting and body treating compositions" (58th), "Coherent light generators" (69th), and "Compositions" (53rd).

As measured by the Authority Score, PI-inventors' patents had generally higher rankings than the number of cites, indicating that PI-inventors' patents had relatively higher indirect impact on industrial NSE development. The titles of the highly ranked PI-inventor patents correspond nicely with the content map analysis results. These critical PI-inventors represented the dominant topic areas of NSF-funded NSE research.

The PI-inventors who had the highest number of cites in each of the top 20 NSE fields are listed in Table 17. In 3 of these fields the top PI-inventors were ranked higher than 20. George M. Whitesides (Harvard University) and Paul K. Hansma (University of California) were the most influential PI-inventors. George M. Whitesides was arguably the most influential PI-inventor by

Table 16. Critical patent analysis: Authority Score

Rank	US patent classification	Name	Number of patents	Highest ranked PI-inventor patent measured by Authority score
1	435	Chemistry: molecular biology and microbiology	7946	32nd: [5106729] "Method for visualizing the base sequence of nucleic acid polymers." Arizona Board of Regents acting on behalf of Arizona State University. Authority Score = 88.90502
2	514	Drug, bio-affecting and body treating compositions	6183	40th: [5157032] "Mixed ligand complexes and uses thereof as binding agents and probes to DNA." The Trustees of Columbia University in the City of New York. Authority Score = 6.20386
3	424	Drug, bio-affecting and body treating compositions	4683	58th: [5639473] "Methods for the preparation of nucleic acids for in vivo delivery." Vivorx Pharmaceuticals, Inc. Authority Score = 8.721781
4	250	Radiant energy	4657	4th: [4935634] "Atomic force microscope with optional replaceable fluid cell." The Regents of the University of California. Authority Score = 490.1931
5	428	Stock material or miscellaneous articles	3939	1st: [4728591] "Self-assembled nanometer lithographic masks and templates and method for parallel fabrication of nanometer scale multidevice structures." Trustees of Boston University. Authority Score = 165.5829
6	257	Active solid-state devices (e.g., transistors, solid-state diodes)	3933	16th: [5093699] "Gate adjusted resonant tunnel diode device and method of manufacture." Texas A & M University System. Authority Score = 16.50901
7	438	Semiconductor device manufacturing: process	3877	9th: [5618760] "Method of etching a pattern on a substrate using a scanning probe microscope." The Board of Trustees of the Leland Stanford, Jr. University. Authority Score = 30.16755
8	536	Organic compounds – part of the class 532–570 series	3756	8th: [4500707] "Nucleosides useful in the preparation of polynucleotides." University Patents, Inc. Authority Score = 152.8311
9	530	Chemistry: natural resins or derivatives; peptides or proteins; lignins or reaction products thereof	3753	16th: [5620850] "Molecular recognition at surfaces derivatized with self-assembled monolayers." President and Fellows of Harvard College. Authority Score = 28.0039
10	359	Optics: systems (including communication) and elements	3404	21st: [5479024] "Method and apparatus for performing near-field optical microscopy." The Regents of the University of California. Authority Score = 16.1751
11	427	Coating processes	3265	20th: [5512131] "Formation of microstamped patterns on surfaces and derivative articles." President and Fellows of Harvard College. Authority Score = 18.20165
12	436	Chemistry: analytical and immunological testing	3027	20th: [5106729] "Method for visualizing the base sequence of nucleic acid polymers." Arizona Board of Regents acting on behalf of Arizona State University. Authority Score = 88.90502
13	430	Radiation imagery chemistry: process, composition, or product thereof	2983	1st: [4728591] "Self-assembled nanometer lithographic masks and templates and method for parallel fabrication of nanometer scale multi-device structures." Trustees of Boston University. Authority Score = 165.5829
14	356	Optics: measuring and testing	2957	19th: [5479024] "Method and apparatus for performing near-field optical microscopy." The Regents of the University of California. Authority Score = 16.1751

Table 16. (Continued)

15	365	Static information storage and retrieval	2310	47th: [5228001] "Optical random access memory." Syracuse University. Authority Score = 6.262227
16	327	Miscellaneous active electrical nonlinear devices, circuits, and systems	2286	24th: [5475341] "Sub-nanoscale electronic systems and devices." Yale University. Authority Score = 2.072026
17	204	Chemistry: electrical and wave energy	1864	1st: [5202004] "Scanning electrochemical microscopy." Digital Instruments, Inc. Authority Score = 436.3328
18	422	Chemical apparatus and process disinfecting, deodorizing, preserving, or sterilizing	1829	23rd: [5620850] "Molecular recognition at surfaces derivatized with self-assembled monolayers." President and Fellows of Harvard College. Authority Score = 28.0039
19	372	Coherent light generators	1775	69th: [5036220] "Nonlinear optical radiation generator and method of controlling regions of ferroelectric polarization domains in solid state bodies." Leland Stanford Junior University. Authority Score = 0.4296076
20	252	Compositions	1680	53rd: [5324457] "Devices and methods for generating electrogenerated chemiluminescence." Board of Regents, The University of TX System. Authority Score = 1.09404

this measure. He was highly ranked in 4 fields, the most prominent ones being "Semiconductor device manufacturing process" (ranked 13th with 120 citations) and "Chemistry: natural resins or derivatives; peptides or proteins; lignins or reaction products thereof" (ranked 13th with 216 citations). Paul K. Hansma received 427 citations and was ranked 5th in the field "Radiant energy."

PI-inventors had low rankings in the following fields: "Drug, bio-affecting and body treating compositions" (486th), "Coherent light generators" (246th), and "Optics: measuring and testing" (223rd).

Table 18 presents the PI-inventors who had the highest ranking measured by the Authority Score. In 6 of these fields the top PI-inventors were ranked 20th and above. Paul K. Hansma was again one of the most important PI-inventor. He was highly ranked in 3 fields, the most prominent one of which was still "Radiant energy" (ranked 4th). The other most influential PI-inventor was Noel A. Clark of Boston University, who was ranked 4th in the field "Stock material or miscellaneous articles." PI-inventors had relatively lower Authority Scores in the fields "Coherent light generators" (159th) and "Chemical apparatus and process disinfecting, deodorizing, preserving, or sterilizing" (97th).

PI-inventors have relatively higher indirect impact as measured by the critical patent analysis results. The strongest and weakest NSE fields for the PI-inventors and their patents were consistent across the results presented in Tables 15–18, confirming again the comparison between award and patent content maps discussed previously.

Sample patent citation networks

To further illustrate the relative position of PI-inventors, we selected three representative NSE fields and visualized the patent citation networks of these fields. For an NSE field, we selected a particular minimum number of cites and obtain a set of core patents of a manageable size to visualize. The inventors of these core patents (represented by circles in the network) were identified. Inventors who had at least two patents in the core set were shown in the network as triangles. In these networks, links between patents represent the patent citation. A link with the form "patent A → patent B" represents that patent A had been

Table 17. Critical inventor analysis: number of cites

Rank	US patent classification	Name	Number of inventors	Highest ranked PI-inventor measured by Number of Cites
1	435	Chemistry: molecular biology and microbiology	10971	28th: [Whitesides, George M.] President and Fellows of Harvard College Number of cites = 468
2	514	Drug, bio-affecting and body treating compositions	8526	486th: [Barton, Jacqueline K.] The Trustees of Columbia University in the City of New York Number of Cites = 18
3	424	Drug, bio-affecting and body treating compositions	6442	94th: [Suslick, Kenneth S.] University of Illinois, Vivorx Pharmaceuticals, Inc. Number of Cites = 106
4	250	Radiant energy	6238	5th: [Hansma, Paul K.] The Regents of the University of California Number of Cites = 427
5	428	Stock material or miscellaneous articles	6039	33rd: [Gordon, Roy G.] Harvard College Number of Cites = 194
6	257	Active solid-state devices (e.g., transistors, solid-state diodes)	5955	34th: [Reed, Mark A.] Yale University Number of Cites = 127
7	438	Semiconductor device manufacturing: process	5808	13th: [Whitesides, George M.] President and Fellows of Harvard College Number of Cites = 120
8	536	Organic compounds – part of the class 532–570 series	5220	26th: [Caruthers, Marvin H.] University Patents, Inc. Number of cites = 133
9	530	Chemistry: natural resins or derivatives; peptides or proteins; lignins or reaction products thereof	5108	13th: [Whitesides, George M.] President and Fellows of Harvard College Number of Cites = 216
10	359	Optics: systems (including communication) and elements	4747	81st: [Gordon, Roy G.] The President and Fellows of Harvard College Number of Cites = 56
11	427	Coating processes	4369	63rd: [Gordon, Roy G.] The President and Fellows of Harvard College Number of Cites = 114
12	436	Chemistry: analytical and immunological testing	4223	26th: [Bard, Allen J.] The University of Texas System, Board of Regents Digital Instruments, Inc., IGEN International Inc. Number of Cites = 322 26th: [Whitesides, George M.] President and Fellows of Harvard College Numbers of cites = 322
13	430	Radiation imagery chemistry: process, composition, or product thereof	3916	223rd: [Zaidi, Saleem H.] The University of New Mexico Numbers of Cites = 46
14	356	Optics: measuring and testing	3518	65th: [Maris, Humphrey J.] Brown University Research Foundation Number of cites = 49
15	365	Static information storage and retrieval	3200	121st: [Birge, Robert R.] Syracuse University Number of Cites = 35
16	327	Miscellaneous active electrical nonlinear devices, circuits, and systems	2868	86th: [Reed, Mark A.] Yale University Number of Cites = 18
17	204	Chemistry: electrical and wave energy	2482	35th: [Lindsay, Stuart M.] Arizona State University, Molecular Imaging Corporation, The United States of America as represented by the Secretary of the Navy Number of cites = 84 35th: [Zare, Richard N.] The Board of Trustees of the Leland Stanford Junior College, Number of Cites = 84
18	422	Chemical apparatus and process disinfecting, deodorizing, preserving, or sterilizing	2438	66th: [Whitesides, George M.] President and Fellows of Harvard College Number of Cites = 101
19	372	Coherent light generators	2260	246th: [Fejer, Martin M.] Stanford University Number of Cites = 15
20	252	Compositions	2044	54th: [Bard, Allen J.] University of Texas Number of Cites = 36

Table 18. Critical inventor analysis: Authority Score

Rank	US patent classification	Name	Number of inventors	Highest ranked PI-inventor measured by Authority Score
1	435	Chemistry: molecular biology and microbiology	10971	52nd: [Lindsay, Stuart M.] Arizona State University, Molecular Imaging Corporation AuthScore = 355.6201
2	514	Drug, bio-affecting and body treating compositions	8526	78th: [Barton, Jacqueline K.] Columbia University AuthScore = 18.61158
3	424	Drug, bio-affecting and body treating compositions	6442	69th: [Suslick, Kenneth S.] University of Illinois, Vivorx Pharmaceuticals, Inc. AuthScore = 47.45637
4	250	Radiant energy	6238	4th: [Hansma, Paul K.] the University of California AuthScore = 4208.508
5	428	Stock material or miscellaneous articles	6039	4th: [Clark, Noel A.] Boston University AuthScore = 662.3314 4th: [Rothschild, Kenneth J.] AmberGen Inc, Boston University AuthScore = 662.3314
6	257	Active solid-state devices (e.g., transistors, solid-state diodes)	5955	35th: [Kirk, Wiley P.] Texas A & M University System, Texas Instruments Incorporated AuthScore = 99.05406
7	438	Semiconductor device	5808	14th: [Minne, Stephen C.] Stanford University, NanoDevices, Inc. University AuthScore = 90.50266
8	536	Organic compounds – part of the class 532–570 series	5220	9th: [Caruthers, Marvin H.] University Patents, Inc. AuthScore = 466.1678
9	530	Chemistry: natural resins or derivatives; peptides or proteins; lignins or reaction products thereof	5108	29th: [Whitesides, George M.] Harvard College AuthScore = 120.134
10	359	Optics: systems (including communication) and elements	4747	82th: [Hansma, Paul K.] the University of California AuthScore = 16.1751
11	427	Coating processes	4369	61st: [Clark, Noel A.] Boston University AuthScore = 42.54337 61st: [Rothschild, Kenneth J.] AmberGen Inc., Boston University AuthScore = 42.54337
12	436	Chemistry: analytical and immunological testing	4223	82nd: [Lindsay, Stuart M.] Arizona State University Molecular Imaging Corporation AuthScore = 88.90502
13	430	Radiation imagery chemistry: process, composition, or product thereof	3916	9th: [Clark, Noel A.] Boston University AuthScore = 165.5829 9th: [Rothschild, Kenneth J.] AmberGen Inc. Boston University AuthScore = 165.5829
14	356	Optics: measuring and testing	3518	87th: [Hansma, Paul K.] the University of California AuthScore = 16.1751
15	365	Static information storage and retrieval	3200	59th: [Birge, Robert R.] Syracuse University AuthScore = 18.98621
16	327	Miscellaneous active electrical nonlinear devices, circuits, and systems	2868	34th: [Reed, Mark A.] Yale University AuthScore = 4.144051
17	204	Chemistry: electrical and wave energy	2482	7th: [Lindsay, Stuart M.] Arizona State University, Molecular Imaging Corporation AuthScore = 1410.155
18	422	Chemical apparatus and process disinfecting, deodorizing, preserving, or sterilizing	2438	97th: [Whitesides, George M.] Harvard College AuthScore = 34.00076
19	372	Coherent light generators	2260	159th: [Fejer, Martin M.] Stanford University AuthScore = 0.45
20	252	Compositions	2044	43rd: [Bard, Allen J.] University of Texas, Digital Instruments AuthScore = 5.014

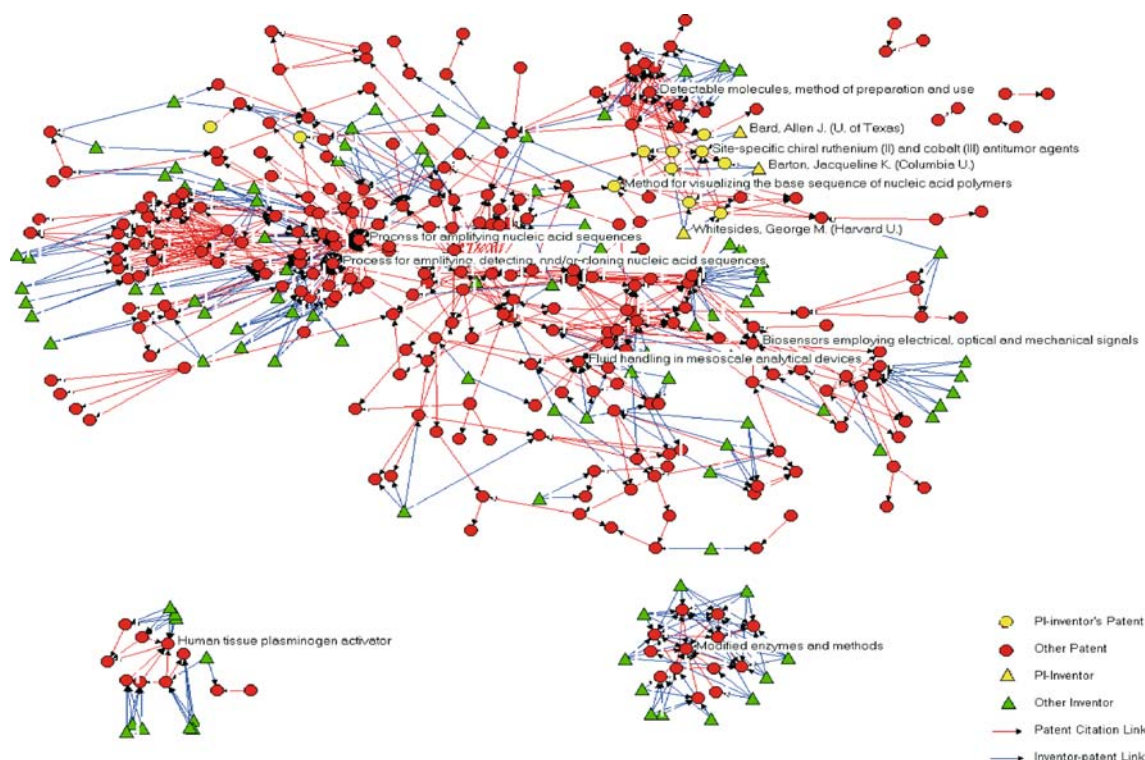


Figure 11. Patent citation network: “Chemistry: molecular biology and microbiology”.

cited by patent B. Links between inventors and patents represent the patent authorship, i.e. “inventor A \rightarrow patent B” represents that A is one of the inventors of patent B. We used the yellow color to mark the PI-inventors and their patents in these networks. We also selectively show the keywords in the titles of the core patents.

a. The citation network for the largest NSE field “Chemistry: molecular biology and microbiology” is given in Figure 11. Only the patents with more than 5 cites are shown. The keywords in the titles of the most important patents include: “detectable molecules, method of preparation and use,” “process for amplifying nucleic acid sequences,” and “fluid handling in mesoscale analytical devices.” The general observation for this field is that PI-inventors and their patents form a closely linked cluster within the largest connected component of the citation network. This PI-inventor cluster includes Allen J. Bard of the University of Texas, Jacqueline K.

Barton of Columbia University, and George M. Whitesides of Harvard University.

b. Figure 12 displays the citation network for the field “Radiant energy,” in which PI-inventors had the strongest positions. The patents shown were cited more than 14 times. The network shows that the core patents in this field form one dense connected component without lower level subclusters. “atomic force microscope,” “scanning ion conductance microscope,” and “scanning tunneling microscope” are the major topics. PI-inventors’ patents were among the top-cited patents covering the central topic of the field, microscope-related topics, for example “atomic force microscope with optional replaceable fluid cell” and “high resolution atomic force microscope”. Paul K. Hansma and Allen J. Bard appeared in this network as well. Stuart M. Lindsay of Arizona State University and Joseph W. Lyding of the University of Illinois also appeared in the network.

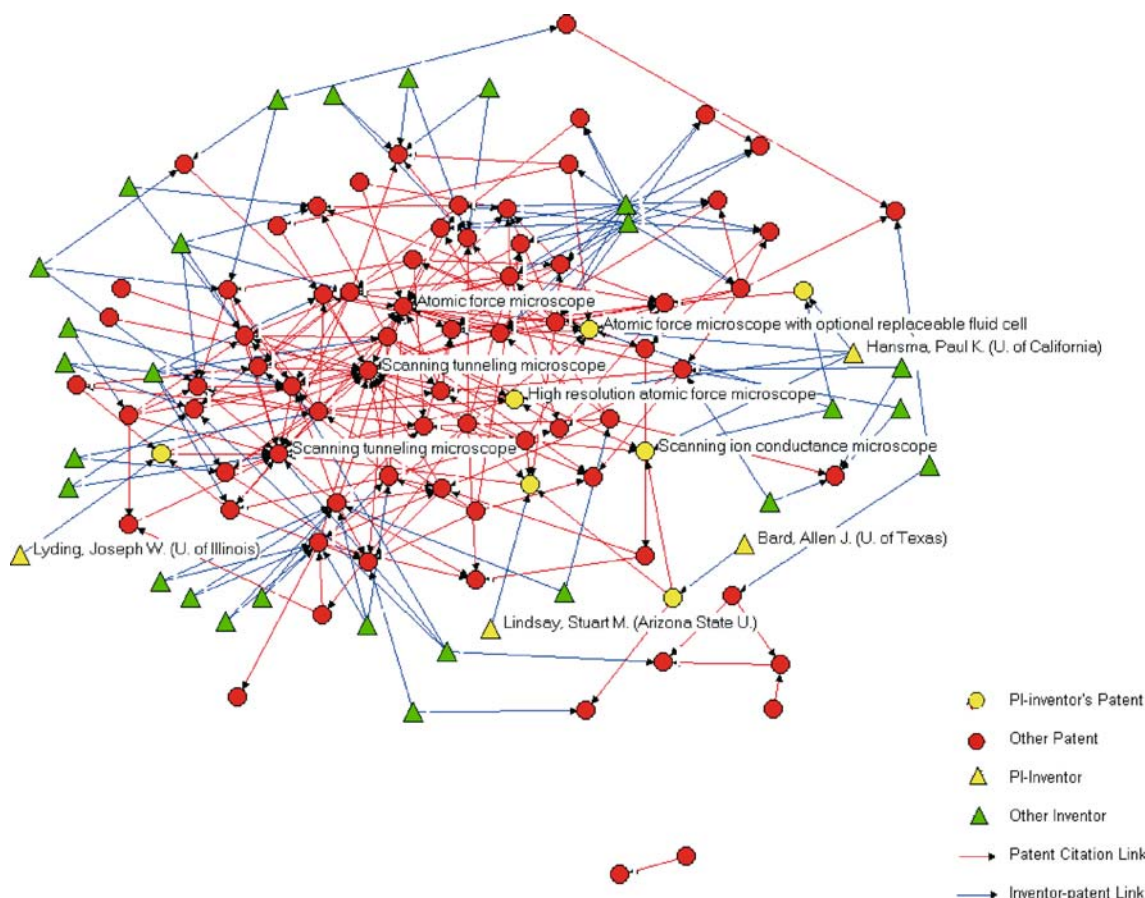


Figure 12. Patent citation network: “Radiant energy”.

c. Figure 13 shows the citation network for a relatively small field among the top 20 NSE fields: “Chemistry: electrical and wave energy.” Patents shown were cited more than once. Important topics in this field include “capillary gel electrophoresis columns”, “laser-excitation fluorescence detection electrokinetic separation,” and “silicon semiconductor wafer for analyzing micronic biological samples.” The network shows that three patents by Jonathan V. Sweedler and Richard N. Zare of Stanford University occupied the central places in the largest connected component. Two other PI-inventors’ patents were in an isolated small cluster, which might share some common ideas in “Scanning electrochemical microscopy.”

Statistical hypothesis testing

The impact of NSF-funded PI-inventors as a group has been statistically compared with other groups of inventors for the following hypotheses:

- H1: Patents associated with NSF-funded PI-inventors had a higher number of cites measure than patents associated with other groups of inventors.
- H2: Patents associated with NSF-funded PI-inventors had a higher Authority Score measure than patents associated with other groups of inventors.
- H3: NSF-funded PI-inventors had a higher number of cites measure than other groups of inventors.

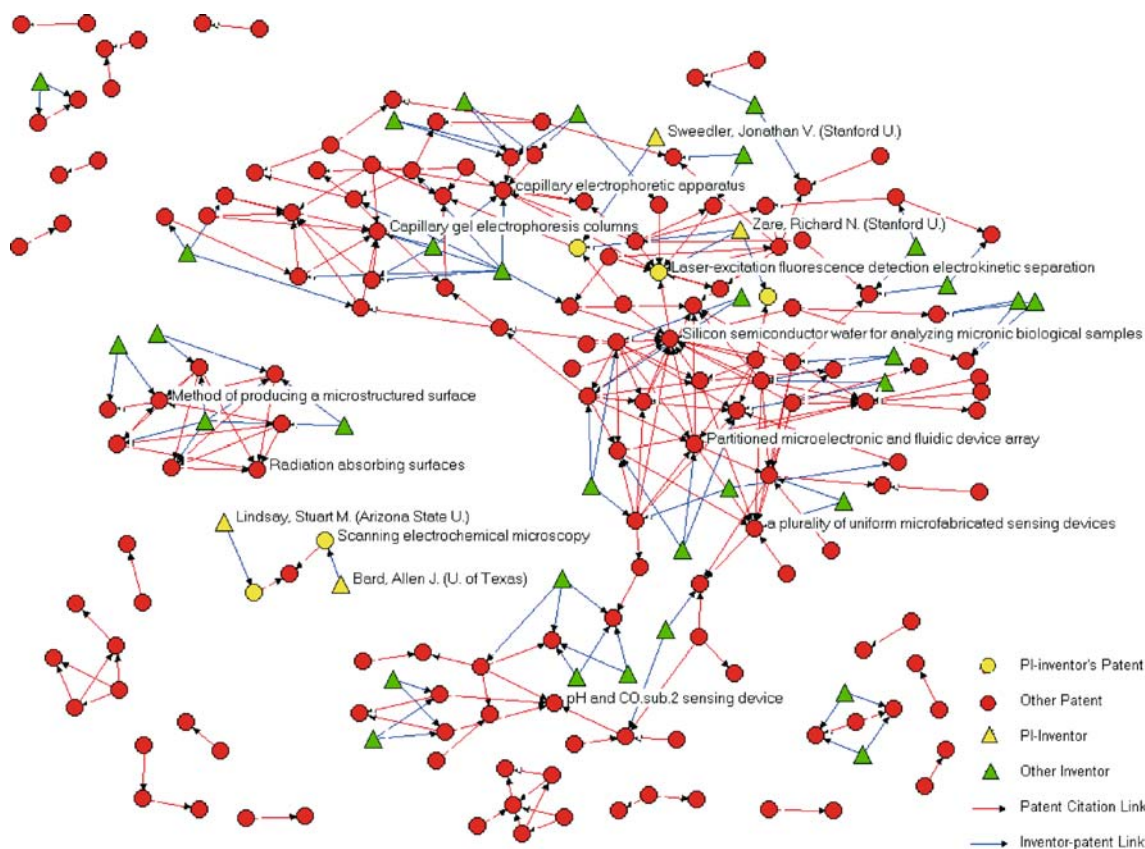


Figure 13. Patent citation network: “Chemistry: electrical and wave energy”.

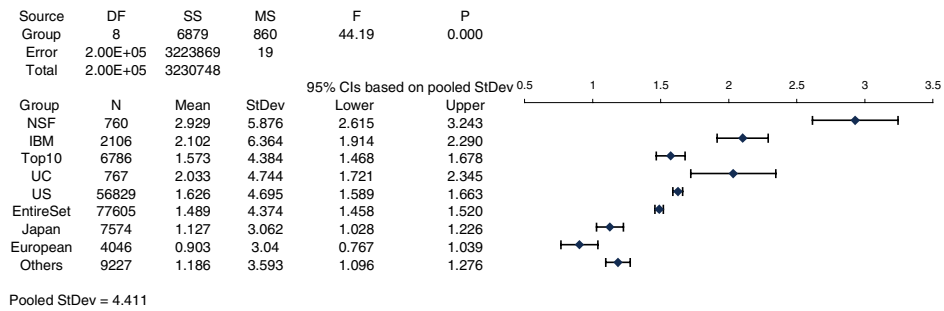
- H4: NSF-funded PI-inventors had a higher Authority Score measure than other groups of inventors.

We selected nine groups of inventors from the top assignee countries and institutions between 1976 and 2002:

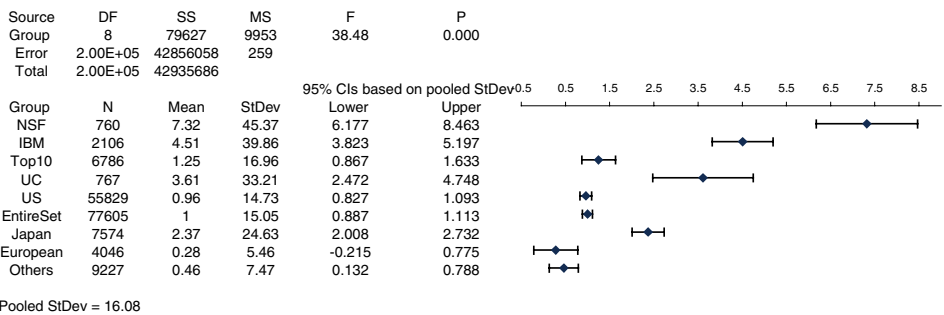
1. NSF: PI-inventors and their patents (760 patents and 307 inventors)
2. IBM: Inventors and patents of IBM (2,106 patents and 2,756 inventors)
3. Top10: Inventors and patents of top 10 institutions (6,786 patents and 6,650 inventors)
4. UC: Inventors and patents of the University of California (the top academic institute in NSE-related patenting, 767 patents and 894 inventors)
5. US: Inventors and patents of the United States (55,829 patents and 78,227 inventors)
6. EntireSet: Inventors and patents of the entire patent dataset (77,605 patents and 108,378 inventors)
7. Japan: Inventors and patents of Japan (7,574 patents and 14,837 inventors)
8. European: Inventors and patents of European countries (4,046 patents and 9,560 inventors)
9. Others: Random inventors and patents of countries other than U.S., Japan, and European countries (9,227 patents and 6,385 inventors)

Then, we conducted *Analysis of Variance* (ANOVA) tests (using the Minitab software, <http://www.minitab.com>) to validate the four hypotheses. The analysis results are shown in Figure 14. All four analyses had p -values of 0.000, indicating significant differences in criticalness measures across different comparison groups.

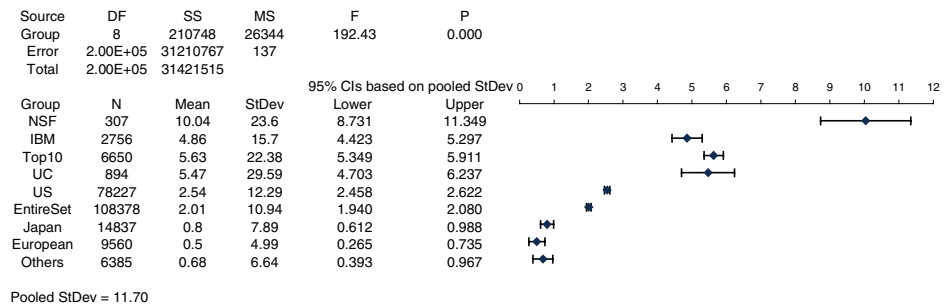
Figure 14(a) shows that hypothesis H1 was supported at the 95-percent level. NSF-funded



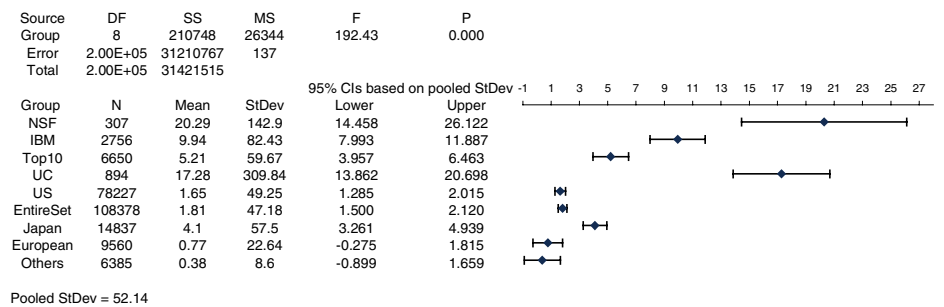
(a) H1: Number of cites per NSE-related patent



(b) H2: Authority Score per NSE-related patent



(c) H3: Number of cites per NSE-related inventor



(d) H4: Authority Score per NSE-related inventor

Figure 14. Comparison between the impact of NSF funded PI-inventors and other groups.

PI-inventors have patents with significantly larger number of cites (about 3 cites in average) compared to other groups (about 1.5 cites for all patents), followed by the IBM and UC groups. US, EntireSet and Top10 are the next three groups. US patents have larger number of cites than patents of the EntireSet. Patents of Japan, European, and Others have a smaller number of cites compared to other groups, while patents of the Others group have larger number of cites than the European group.

Figure 14(b) illustrates that H2 was also supported. The Authority Scores of NSF-funded PI-inventor patents are significantly larger (about 7.5 in average) than the scores of patents of other groups (less than 1 for all patents). Similar group ordering was observed as shown in Figure 14(a), except that patents of the Japan group had relatively higher impact when measured by the Authority Score (comparable level as the UC group).

Figure 14(c) shows that H3 had strong support from our data. NSF-funded PI-inventors had a significantly larger number of cites (about 10 in average) than all other groups (about 2 for all inventors). Inventors of Top10, IBM, and UC were the second category, possessing quite significantly larger number of cites than the remaining groups. Both US and EntireSet were separate from the last category of groups, which includes Japan, European, and Others.

Figure 14(d) shows that H4 was also supported by our data. Only the UC inventors' Authority Score interval (about 17 in average) had overlap with that of the NSF funded PI-inventors (about 20 in average), while the Entire Set is much lower (about 1 for all inventors). IBM inventors had significantly larger Authority Score than Top10 inventors, while Figure 14(c) shows that Top10 inventors had larger number of cites. Similar to the pattern in Figure 14(a) and 14(b), Japan inventors had relatively higher impact when measured by Authority Scores than by number of cites, indicating nanotechnology development in Japan had relatively greater indirect impact than direct impact in the entire NSE field. Inventors of the remaining groups had comparable Authority Scores: US, EntireSet, European, and Others.

The statistical analysis suggests that the NSF-funded PI-inventors had significantly higher impact on NSE development than other compar-

ison groups. This result may be a reflection of the larger impact of long-term fundamental research sponsored by NSF as compared in average to all research. Also, we observe that PI-inventors have been important players in the NSE field as reflected in the patent citation data, although our results do not provide direct evidence of a causal relationship between NSF funding and the high impact of PI-inventors.

Conclusions

The NSF funding of NSE research in the interval 1991–2002 as described by the NSF awards and its impact on technological innovation as described by the USPTO patents have been analyzed and correlated in this paper. Using bibliometric, content map, critical inventor/patent and citation network analysis, we have identified several general trends, the key players, and the evolution of technology topics in the NSE-related award and patent activities. The relative contribution and impact of NSF-funded researchers in the field of nanotechnology has been compared with other groups such as researchers in top institutions and universities with active nanotechnology developments, and all inventors with USPTO patents assigned to the United States, Japan, and European countries.

The key findings are:

- (1) Nanotechnology-related R&D has grown rapidly especially after 1997 and 2001, as reflected in both NSF awards and USPTO patents.
- (2) The NSF-funded research and patents all have substantial overlapping in the NSE field key technology topics such as materials and microscopes. NSF-funded research does not generally overlap well with several other topics in NSE-related patents, particularly the pharmaceutical research where industry funding is leading the major development.
- (3) NSF-funded researchers have significantly higher impact in nanotechnology development than other reference groups as reflected in the patent citation data.

The methodology presented in this paper aims to correlate the publicly funded research and commercial research and development activities. The

results have relevance in the evaluation of research programs and in research funding policy. A limitation of the analysis presented in this paper is that the causal relationship between public funding and commercial impact was not analyzed, only the correlation. In future research we plan to use the event study methodology and other approaches to explore the causal relationship and include it in our general analysis framework.

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