

# A longitudinal analysis of nanotechnology literature: 1976–2004

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**Abstract** Nanotechnology research and applications have experienced rapid growth in recent years. We assessed the status of nanotechnology research worldwide by applying bibliographic, content map, and citation network analysis to a data set of about 200,000 nanotechnology papers published in the Thomson Science Citation Index Expanded database (SCI) from 1976 to 2004. This longitudinal study shows a quasi-exponential growth of nanotechnology articles with an average annual growth rate of 20.7% after 1991. The United States had the largest contribution of nanotechnology research and China and Korea had the fastest growth rates. The largest institutional contributions were from the Chinese Academy of Sciences and the Russian Academy of Sciences. The high-impact papers generally described tools, theories, technologies, perspectives, and overviews of nanotechnology. From the top 20 institutions, based on the average number of paper citations in 1976–2004, 17 were in the United States, 2 in France and 1 in Germany. Content map analysis

identified the evolution of the major topics researched from 1976 to 2004, including investigative tools, physical phenomena, and experiment environments. Both the country citation network and the institution citation network had relatively high clustering, indicating the existence of citation communities in the two networks, and specific patterns in forming citation communities. The United States, Germany, Japan, and China were major citation centers in nanotechnology research with close inter-citation relationships.

**Keywords** Bibliographic analysis · Citation analysis · Information visualization · Self-organizing maps · Nanoscale science and engineering · Nanotechnology papers · Research and development (R&D) · Technological innovation

## Introduction

Nanotechnology has experienced rapid growth in the last years and produced many research streams (Hullmann 2006). Nanotechnology deeply impacts a wide range of application domains and is estimated to be a critical indicator of a country's technological competence. More than 60 countries have adopted national projects or programs to prompt nanotechnology research (Roco et al. 2000; Roco 2005),

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including all developed countries and many developing countries. The quantitative assessment of nanotechnology R&D status is of interest to governments, private sectors, human development organizations, and nanotechnology researchers. Patent documents and scientific literature can provide indicators for assessment of nanotechnology R&D.

Patent analysis has been widely used in knowledge mapping research (Karki 1997; Oppenheim 2000). A patent analysis framework has been proposed by Huang et al. (2003), which includes bibliographic analysis, content map analysis, and citation network analysis on patents. Longitudinal analysis of nanotechnology patents has been conducted based on this framework (Huang et al. 2003, 2004; Li et al. 2007b). Patent analysis results relate primarily to industry R&D efforts and the applications of nanotechnology.

The scientific literature, on the other hand, documents the knowledge generated primarily by academia. Most previous research used bibliographic analysis of the literature to assess nanotechnology development. Previous studies have identified an exponential growth pattern in nanotechnology publication (Braun et al. 1997). At the same time, new and diverging research topics could be found in the scientific literature, indicating substantial and growing differences among researchers (Porter and Cunningham 1995). Some studies provided snapshots of individual years' publication status. For example, Kostoff et al. (2006a, b) identified the key publications, key authors, journals, institutions, and countries

for 2003. The scientific literature has also been used to assess collaboration and knowledge diffusion in nanotechnology research. Meyer and Persson (1998) found that the nanotechnology field has more interdisciplinary interactions than many other areas of science, while Schummer (2004) argued that the researchers do not show much inter-disciplinary co-authorship collaboration.

Table 1 summarizes previous studies using literature analysis to assess the R&D status of the nanotechnology domain. Compared to patent analysis (Li et al. 2007b; Chen et al. 2008), the literature analysis investigations used fewer analysis tools on limited data, and many of these studies used only bibliographic analysis. There is no recent longitudinal analysis on nanotechnology literature when the domain has experienced rapid growth.

The status of nanotechnology development in science and engineering research is investigated here using the literature documented in the Thomson Science Citation Index Expanded database. We conducted longitudinal research using bibliographic analysis, content map analysis, and citation network analysis in order to discover the strengths and characteristics of the networks of relationships among authors, countries, and institutions.

## Data description and limitations

Since nanotechnology is a multidisciplinary research field, nanotechnology papers are published in a

**Table 1** A summary of previous literature analysis on nanotechnology

Study	Data source	Data collection	Year of data	No. of papers	Analysis
Porter and Cunningham (1995)	INSPEC and SCI	Keyword search on title, abstract, and keywords	1993, 1994, and 1986–1995	3,956 and 1,176	Bibliographic analysis
Braun et al. (1997)	SCI	Keyword search on title	1986–1995	4,152	Bibliographic analysis
Meyer and Persson (1998)	SCI	Keyword search on title	1991–1996	5,430	Bibliographic analysis
Meyer (2001)	SCI	Keyword search on title	1991–1996	5,430	Bibliographic analysis
Schummer (2004)	9 nano-related journals	Random sampling on the papers	2002	609	Co-authorship analysis
Kostoff et al. (2006a)	SCI	Keyword search on title, abstract, and keywords	2003	21,474	Bibliographic analysis
Kostoff et al. (2006b)	SCI	Keyword search on title, abstract, and keywords	2003	21,474	Bibliographic analysis, clustering analysis

variety of journals. Several literature repositories with different focuses and coverage are available worldwide. We examined three major scientific and engineering literature repositories to discern which repository better covers nanotechnology papers.

- The *SCI database* indexes journals in more than 150 disciplines, including Agriculture, Biology, Chemistry, Computer Science, Engineering, Materials Science, Medicine, Physics, Pharmacology, etc. The SCI database currently contains more than 5,900 journals (5,475 journals up to 2005, [http://scientific.thomson.com/ts/media/pdfs/sourcepub-journals/wos\\_scie\\_a5021\\_final.pdf](http://scientific.thomson.com/ts/media/pdfs/sourcepub-journals/wos_scie_a5021_final.pdf)) and provides papers' bibliographic and citation information and abstracts.
- The *Compendex database* indexes 2,925 journals, 2,717 conferences, 63 monographs, and 57 book series (up through March 20, 2007, <http://www.ei.org/documents/CPXsource.pdf>). It provides coverage of engineering and applied science fields such as Agricultural Engineering, Chemical Engineering, Computers, Materials, Applied Physics, etc. Compendex data records contain papers' bibliographic information and abstracts.
- The *Inspec database* covers 4,030 journals (up through January 2007 <http://www.theiet.org/publishing/inspec/support/docs/loj.cfm>), and focuses on Computers, Electrical Engineering, Information Technology, Mechanical Engineering, and Physics. Similar to Compendex, Inspec provides only bibliographic information and abstracts.

Comparing the journals covered by the three databases, we found that SCI and Compendex had 1,476 journals in common (according to a search for matching ISBNs). SCI and Inspec had 1,224 journals in common (according to name match). Compendex and Inspec had 1,320 journals in common (according to name match).

Examination of the three repositories shows that the SCI database has broader disciplinary coverage than the other two repositories, which focus primarily on engineering journals. SCI covers a large number of journals that were collected by Compendex and Inspec (about 50% of Compendex journals and 30% of Inspec journals), primarily high impact journals in the engineering disciplines. In addition, SCI provides paper citation information, which can be used to

study the impact of a given paper. The domain experts we worked with determined that the SCI database provided more comprehensive and more representative coverage of nanotechnology papers, and we therefore chose SCI as the source for our data on nanotechnology papers.

The data acquired from the SCI database are stored in XML (eXtensible Markup Language) format. The data fields are parsed by Thomson ISI. Some of the data fields, including journal names and institution names, are converted to standardized abbreviations in order to make identification easier. However, the SCI database records only surnames and first initials for authors, which are often not sufficient to identify and distinguish individual researchers, particularly Asian researchers. To better distinguish different authors from each other, and to better discern and quantify their individual contributions to the domain, we used both authors' institutions and their names to identify authors. In general, there is seldom a one-to-one mapping between the authors and their affiliations in a paper and in an SCI data record. Different authors on the author list may belong to the same institution. However, the first author's affiliation is usually the first in the institution list, thus allowing us to use the first author name and the first institution to identify first authors. First authors are usually the major contributors to a paper. We used researchers' first-author publications to represent their contributions to the field and to identify key researchers in the domain.

## Data collection

Nanotechnology papers in the SCI database were identified by conducting a keyword search on paper titles, keywords, and abstracts using a list of nanotechnology keywords provided by domain experts (Huang et al. 2003, 2004). The citations to nanotechnology papers from other papers in the SCI database were also retrieved. In total, we identified 213,847 nanotechnology papers published in 4,175 journals from 1976 to 2004. These papers have 120,687 unique first authors from 24,468 institutions in 156 countries/regions.

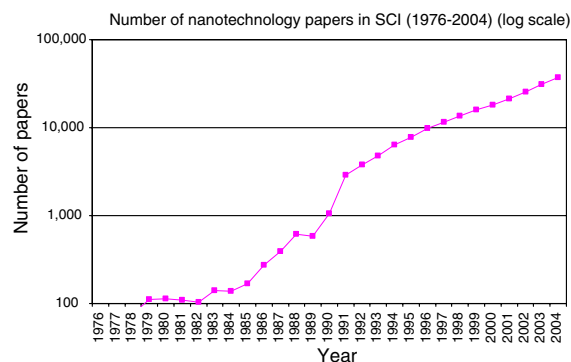
Table 2 and Fig. 1 present the total number of nanotechnology papers published in the SCI database each year. From the log scale graph, we observe that

nanotechnology papers experienced rapid growth in the second half of the 1980s, after the scanning tunneling microscope and atomic force microscope were developed. In the 1990s and the first half of the 2000s, nanotechnology papers continued a quasi-exponential growth pattern which was also found in previous research (Braun et al. 1997). Since 1991, the nanotechnology papers published in each year increased at an annual rate of about 20.7%.

Table 3 shows the first authors with the largest number of publications between 1976 and 2004. Although there may still be some noise in matching author identities, the table roughly shows the key

**Table 2** Number of nanotechnology papers in SCI database (1976–2004)

Year	No. of papers
1976	90
1977	75
1978	77
1979	112
1980	113
1981	109
1982	104
1983	141
1984	138
1985	167
1986	275
1987	393
1988	619
1989	580
1990	1,060
1991	2,900
1992	3,818
1993	4,802
1994	6,422
1995	7,742
1996	9,743
1997	11,651
1998	13,601
1999	15,975
2000	18,085
2001	21,352
2002	25,697
2003	31,003
2004	36,865
Total 1976–2004	213,847



**Fig. 1** Number of nanotechnology papers in SCI database (1976–2004) (log scale)

researchers in the field. The top researchers (first authors) published a similar number of papers. Dr. Zhong Lin Wang (Wang, ZL) of the Georgia Institute of Technology, Dr. Takeo Oku (Oku, T) at Osaka University, and Dr. Achim Muller (Muller, A) of the University of Bielefeld published more papers than other first authors. From the key first authors' affiliations, we observe that the most productive researchers are from the USA (six authors), Japan (five authors), China (two authors), and South Korea (two authors). Singapore, Germany, France, Italy, and England each also have one key researcher as well.

Table 4 shows the countries/regions with the most nanotechnology papers from 1976 to 2004. The United States produced the largest number of nanotechnology papers in this interval; in fact, more than a quarter of the total collection of nanotechnology papers was published by the U.S. authors. Authors in Japan, Germany, and China were also major producers of nanotechnology research, each researcher publishing about one-thirds or fewer of the number of papers published by the U.S. authors.

Table 5 shows the top 20 institutions for nanotechnology paper publication. All top institutions were universities and national research centers rather than private companies. Among these institutions, the Chinese Academy of Sciences and the Russian Academy of Sciences were the most productive. Six of the key institutions are in the United States, five in Japan, three in China, and the remainder in Europe. Although the United States has a large portion of key institutions, the top three most productive institutions are in other countries because of the concentration of research activities in those countries. The US

**Table 3** Top 20 first authors in nanotechnology paper publication (1976–2004)

Rank	First author	Institution	Country/Region	No. of papers
1	Wang, ZL	Georgia Inst Technol	USA	42
2	Oku, T	Osaka Univ	Japan	40
3	Muller, A	Univ Bielefeld	Germany	38
4	Kang, JW	Chung Ang Univ	South Korea	36
5	Xie, WF	Guangzhou Univ	Peoples R China	34
6	Inoue, A	Tohoku Univ	Japan	34
7	Wang, J	New Mexico State Univ	USA	34
8	Sun, CQ	Nanyang Technol Univ	Singapore	32
9	Zhang, J	Chinese Acad Sci	Peoples R China	31
10	Dresselhaus, MS	MIT	USA	30
11	Louzguine, DV	Tohoku Univ	Japan	29
12	Somorjai, GA	Univ Calif Berkeley	USA	29
13	Bhushan, B	Ohio State Univ	USA	28
14	Ugajin, R	Sony Corp	Japan	28
15	Pileni, MP	Univ Paris	France	28
16	Valentini, L	Univ Perugia	Italy	27
17	Alivisatos, AP	Univ Calif Berkeley	USA	27
18	Serizawa, T	Kagoshima Univ	Japan	27
19	Ashton, PR	Univ Birmingham	England	27
20	Choy, JH	Seoul Natl Univ	South Korea	26

institutions showed a relatively lower rank among the top 20 institutions.

Table 6 presents the major journals in which nanotechnology papers were published. “Physical Review B,” “Abstracts of Papers of The American Chemical Society,” and “Applied Physics Letters” are the three sources that published the most nanotechnology papers. Among the top 20 journals, most of them focus on physics, chemistry, and material science, which are the major nanotechnology application areas.

### Bibliographic analysis

We analyzed the collected nanotechnology publications at different analytical unit levels, including:

- authors;
- countries/regions;
- institutions; and
- journals.

Bibliographic analysis was performed to assess the productivity at different analytical units’ and each key analytical unit’s impact on the domain.

### Publication activity analysis

#### Country publication trend

Figures 2 and 3 illustrate the publication trend of the 10 most productive countries in nanotechnology paper publications in the SCI database. Overall, the United States published the most nanotechnology papers, and growth was faster after 1991 than before 1991. Before 1991, the USA, Japan, Germany, France, and England (the United Kingdom) were the major countries in nanotechnology research. After 1991, several additional countries became involved in this arena. China experienced faster growth in the last 10 years than other countries/regions, which made it the second most productive country beginning with 2003. South Korea also showed rapid development after 2000. In four years, it exceeded Italy, Russia, and England to become the 6th most productive country in 2004.

#### Institution publication trend

Figure 4 shows the publication trend of the 10 most productive institutions. Most of the top 10 institutions

**Table 4** Top 20 countries/regions in nanotechnology paper publication (1976–2004)

Rank	Country/Region	No. of papers
1	U.S.	61,068
2	Japan	24,985
3	Germany	21,334
4	Peoples R China	20,389
5	France	13,777
6	England	10,394
7	Russia	7,466
8	Italy	6,879
9	South Korea	6,679
10	Canada	5,017
11	Spain	4,941
12	Switzerland	4,280
13	India	3,869
14	Netherlands	3,635
15	Sweden	3,062
16	China (Taiwan)	2,886
17	Australia	2,788
18	Poland	2,703
19	Israel	2,509
20	Belgium	2,409

show an increase over time, which demonstrates the importance of nanotechnology R&D at these institutions. Among the top institutions, the Chinese Academy of Sciences showed the fastest growth rate; it has also been the most productive institution in the nanotechnology domain since 1999. The Russian Academy of Sciences showed a publication growth rate similar to that of the Chinese Academy of Sciences prior to 1999. However, in the 21st century, its growth slowed and it became the second most productive institution. The other top institutions, including the University of Tokyo, University of Illinois, Osaka University, etc., displayed similar growth trends.

#### Journal publication trend

Figure 5 illustrates the publication trend of the top 10 nanotechnology journals, most of which show quasi-exponential growth in the number of publications over time.

However, the number of nanotechnology papers published in “Surface Science” and “Thin Solid Films”

**Table 5** Top 20 institutions in nanotechnology paper publication (1976–2004)

Rank	Institution	Country/Region	No. of Papers
1	Chinese Acad Sci	Peoples R China	5,858
2	Russian Acad Sci	Russia	3,720
3	Univ Tokyo	Japan	2,465
4	CNRS <sup>a</sup>	France	2,395
5	Univ Paris	France	2,374
6	Osaka Univ	Japan	2,134
7	Tohoku Univ	Japan	2,123
8	Univ Illinois	USA	1,960
9	Univ Calif Berkeley	USA	1,809
10	MIT	USA	1,595
11	Tokyo Inst Technol	Japan	1,477
12	Univ Cambridge	England	1,451
13	Univ Sci & Technol China	Peoples R China	1,445
14	CSIC <sup>b</sup>	Spain	1,439
15	Univ Texas	USA	1,438
16	Tsing Hua Univ	Peoples R China	1,387
17	UC-Santa Barbara	USA	1,322
18	Kyoto Univ	Japan	1,309
19	Harvard Univ	USA	1,292
20	CNR <sup>c</sup>	Italy	1,266

<sup>a</sup> CNRS (France) = Centre national de la recherche scientifique (National Scientific Research Center)

<sup>b</sup> CSIC (Spain) = Consejo Superior de Investigaciones Científicas (Spanish National Research Council)

<sup>c</sup> CNR (Italy) = Consiglio Nazionale delle Ricerche (National Research Council)

slowed after 1996. In “Surface Science,” the number of nanotechnology papers published leveled off after 1996. This phenomenon may indicate a change in the journal’s focus.

#### Impact analysis

In addition to assessing paper publication trends, we analyzed the impacts of different analytical units, including author, country, institution, and journal. High impact papers are identified through the number of citations they received. The high impact analytical units are identified according to the average number of cites per paper they have. The number of cites of a paper is counted from all successive years of the

**Table 6** Top 20 journals in nanotechnology paper publication (1976–2004)

Rank	Journal	No. of papers
1	Physical Review B	8,207
2	Abstracts of Papers of the American Chemical Society	7,636
3	Applied Physics Letters	7,056
4	Langmuir	5,167
5	Journal of Applied Physics	4,732
6	Surface Science	4,362
7	Journal of Physical Chemistry B	3,754
8	Physical Review Letters	3,353
9	Journal of the American Chemical Society	2,809
10	Thin Solid Films	2,710
11	Journal of Vacuum Science & Technology B	2,583
12	Japanese Journal of Applied Physics Part 1—Regular Papers Short Notes & Review Papers	2,317
13	Applied Surface Science	2,189
14	Journal of Crystal Growth	1,969
15	Chemistry of Materials	1,930
16	Journal of Magnetism and Magnetic Materials	1,807
17	Chemical Physics Letters	1,786
18	Journal of Chemical Physics	1,723
19	Macromolecules	1,578
20	Advanced Materials	1,495

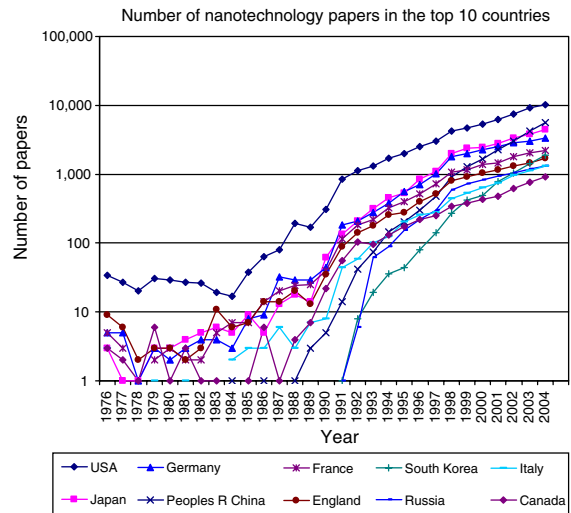
respective date of paper publication until 31 December 2004.

High impact papers

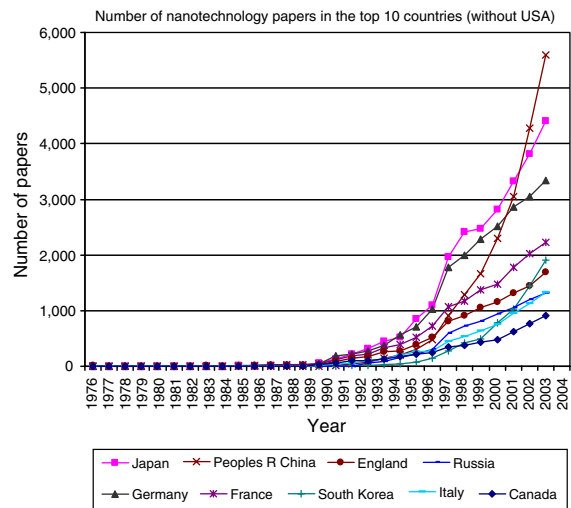
Table 7 shows the most cited, high impact papers. We observe that most of the papers on this list addressed tools, theories, technologies, perspectives, and overviews of nanotechnology. Although the top 20 papers were published by different authors, ten of them were from institutions in the United States, while the others were mainly from European countries.

High impact authors

Table 8 presents the authors with the largest average number of citations to their papers, for authors having

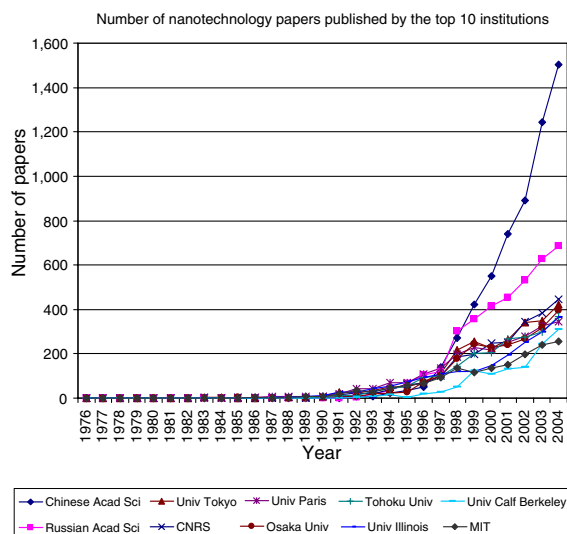


**Fig. 2** Top 10 countries/regions in nanotechnology paper publications (1976–2004) (log scale)



**Fig. 3** Top 10 countries/regions (without USA) in nanotechnology paper publications (1976–2004)

published at least three papers. In the list, most of the authors did not publish a large number of papers. However, other papers cited their papers quite often, indicating the high quality of these publications. The paper authored by Dr. Gerd Binnig (Binnig, G) in IBM have a significant higher average number of cites than other authors' papers. According to the authors' institutions, 16 out of the top 20 authors were from the USA, while the others were from Europe.

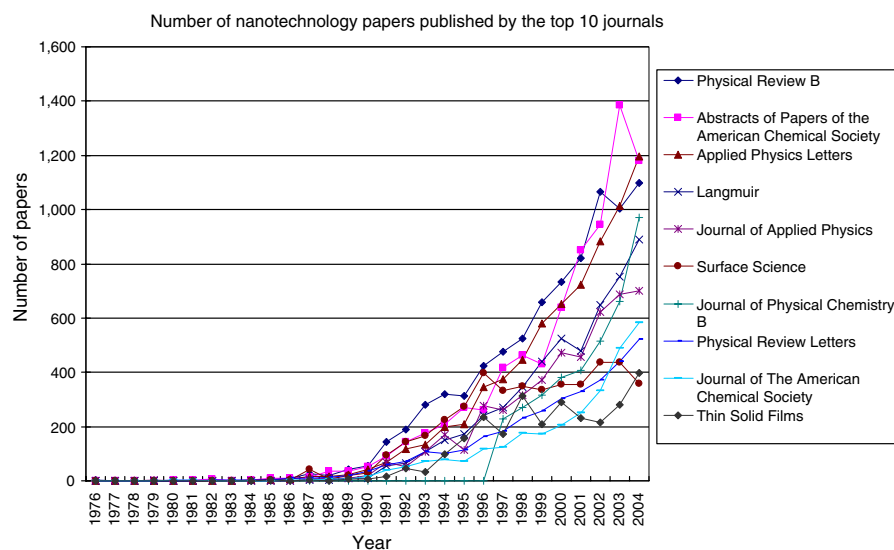


**Fig. 4** Top 10 institutions in nanotechnology paper publications (1976–2004)

### High impact countries

Table 9 shows the top 20 countries with more than 200 papers whose papers were most frequently cited per paper in literature (based on average number of cites per paper). Papers from Switzerland were cited the most frequently per paper. The United States, England, Germany, and France had both a high average number of cites and a high number of papers published.

**Fig. 5** Top 10 journals in nanotechnology paper publications (1976–2004)



### High impact institutions

Table 10 reports the institutions with more than 100 papers with the highest average number of cites. The papers from the AT&T Bell Labs, European Mol Biol Lab, and Harvard University were cited more than other institutions. University of California Berkeley, MIT, University of California Santa Barbara, and Harvard University had more publications than other high impact institutions. In the list, 17 of the institutions were in the United States, two in France and one in Germany. Most of the highly cited institutions were universities.

### High impact journals

Table 11 shows the top 20 journals (publishing more than 20 papers) most frequently cited by nanotechnology papers. Some famous journals such as Cell, Science, and Nature became very recognized in nanotechnology research. Although most of the highly cited journals did not contain a large number of papers, Science, Nature, and “Journal of Physical Chemistry” published significant more nanotechnology papers than other journals. In this list, most of the journals covered broad topics on Physics and Chemistry, such as “Chemical Reviews,” “Reviews of Modern Physics,” “Advances in Physics,” etc. Apparently, when a researcher in another domain wants to cite nanotechnology papers, he tends to look in more general journals than specific ones.



**Table 7** Most cited papers

Rank	Paper title	First author	Institution (Country)	No. of cites
1	Atomic Force Microscope	Binnig, G	IBM Corp (USA)	4,178
2	Observation of Bose-Einstein Condensation in a Dilute Atomic Vapor	Anderson, MH	Univ Colorado (USA)	2,291
3	A Low-Cost, High-Efficiency Solar-Cell Based on Dye-Sensitized Colloidal TiO <sub>2</sub> Films	Oregan, B	Swiss Fed Inst Technol (Switzerland)	1,941
4	FLICE, A Novel FADD-homologous ICE/CED-3-Like Protease, is Recruited to the CD95 (Fas/APO-1) Death-Inducing Signaling Complex	Muzio, M	German Canc Res Ctr (Germany)	1,893
5	Theory of Self-Assembly of Hydrocarbon Amphiphiles into Micelles and Bilayers	Israelachvili, JN	Australian Natl Univ (Austria)	1,691
6	Crystalline Ropes of Metallic Carbon Nanotubes	Thess, A	Rice Univ (USA)	1,635
7	Semiconductor Clusters, Nanocrystals, and Quantum Dots	Alivisatos, AP	Univ Calif Berkeley (USA)	1,587
8	Formation and Structure of Self-Assembled Monolayers	Ulman, A	Polytech Inst New York (USA)	1,574
9	Mass Spectrometric Sequencing of Proteins from Silver Stained Polyacrylamide Gels	Shevchenko, A	European Molec Biol Lab (Germany)	1,522
10	Perspectives in Supramolecular Chemistry—From Molecular Recognition Towards Molecular Information-Processing and Self-Organization	Lehn, JM	Coll France (France)	1,447
11	Synthesis and Characterization of Nearly Monodisperse CdD (E = S, Se, Te) Semiconductor Nanocrystallites	Murray, CB	MIT (USA)	1,348
12	Fuzzy Nanoassemblies: Toward Layered Polymeric Multicomposites	Decher, G	Inst Charles Sadron (France)	1,345
13	Nanocrystalline Materials	Gleiter, H	Inst Neue Mat (France)	1,294
14	Improved Assay for Nanomole Amounts of Inorganic-Phosphate	Lanzetta, PA	CUNY (USA)	1,268
15	Theory of the Scanning Tunneling Microscope	Tersoff, J	AT&T Bell Labs (USA)	1,200
16	3-Dimensional Structure of Myosin Subfragment-1—A Molecular Motor	Rayment, I	Univ Wisconsin (USA)	1,195
17	What If—A Molecular Modeling and Drug Design Program	Vriend, G	State Univ Groningen (Netherlands)	1,163
18	Setor—Hardware-Lighted 3-Dimensional Solid Model Representations of Macromolecules	Evans, SV	Univ British Columbia (Canada)	1,074
19	Conversion of Light to Electricity by cis-X2Bis(2,2'-bipyridyl-4,4'-dicarboxylate)ruthenium(II) Charge-Transfer Sensitizers (X = Cl-, Br-, I-, Cn-, and SCN) on Nanocrystalline TiO <sub>2</sub> Electrodes	Nazeeruddin, MK	Ecole Polytech Fed Lausanne (Switzerland)	1,055
20	Synthesis, Structure, and Properties of Model Organic-Surfaces	Dubois, LH	Univ Illinois (USA)	1,029

## Content map analysis

In addition to bibliographic analysis, we employed content map analysis techniques to visualize the major research topics and represent their evolution over time. Figure 6 illustrates the process of generating a content map for a set of documents. Research topics, represented by keywords in the documents title and abstracts, are first extracted using a Natural Language Processing tool, the Arizona Noun Phraser, according to linguistic patterns (Tolle and Chen 2000). Next, the topics are organized by the multi-

level self-organization map algorithm (Chen et al. 1996; Ong et al. 2005). This algorithm calculates topic similarities according to their co-occurrence patterns in documents and merges similar topics together. Due to the random factors in the algorithm, the organized (and combined) topics may contain some noise. The topic map interface visualizes the topic regions on a hierarchical content map, where the topics are positioned geographically based on their similarity. Conceptually, the closer the relationship among the technology topics, the closer the geographic positions will be. The sizes of the regions

**Table 8** Top 20 first authors with more than two papers (1976–2004) according to the average number of cites by Dec. 2004

Rank	First author	Institution	Country/Region	No. of papers	Average no. of cites
1	Binnig, G	IBM Corp	USA	5	896.00
2	Ulman, A	Polytech Inst New York	USA	3	536.33
3	Wilm, M	European Molec Biol Lab	Germany	3	512.67
4	Murray, CB	MIT	USA	4	510.50
5	Huo, QS	Univ Calif Santa Barbara	USA	3	454.33
6	Rayment, I	Univ Wisconsin	USA	3	406.33
7	Lehn, JM	Coll France	France	4	381.00
8	Tans, SJ	Delft Univ Technol	Netherlands	6	347.50
9	Huang, MH	Univ Calif Berkeley	USA	3	327.33
10	Journet, C	Univ Montpellier	France	3	322.00
11	Bockrath, M	Univ Calif Berkeley	USA	3	306.33
12	Prime, KL	Harvard Univ	USA	3	298.67
13	Kumar, A	Harvard Univ	USA	5	264.00
14	Leininger, S	Univ Utah	USA	3	261.67
15	Peng, XG	Univ Calif Berkeley	USA	4	260.00
16	Messersmith, PB	Cornell Univ	USA	3	255.00
17	Liu, J	Rice Univ	USA	3	248.33
18	Tanev, PT	Michigan State Univ	USA	4	243.50
19	Yang, PD	Univ Calif Santa Barbara	USA	4	240.50
20	Dabbousi, BO	MIT	USA	3	234.67

are proportional to the number of documents assigned to the topics.

We generated content maps for two time periods: 1990–1999, and 2000–2004. Since records from 1976 to 1989 in the SCI database do not contain abstracts, we were unable to generate a meaningful content map for that time period. The SOM (Self-Organizing Map) algorithm used for content map creation chooses topic names according to the number of papers. Since some topics may have different numbers of papers in different time periods, it is possible that they appear as standalone regions for one time period and merge with each other in another time period. However, the final topics selected by the SOM algorithm always represent the dominant topic in the time period.

In order to identify the evolution of research topics over time, we computed a growth rate for each topic area. The growth rate is calculated as the ratio between the number of documents in 2000–2004 and the number of documents in 1990–1999 for a topic. If the topic appears only in one time period, then the growth rate is not able to be calculated. However, the disappearance of the topic shows the relative

decrease of the topic in paper publication. For all the documents, we define a baseline growth rate as the ratio between the total number of documents in the two time periods, which indicates the overall (average) increase or decrease of paper publication. The growth rates are visualized on the content map by different colors. A topic region with a growth rate similar to the baseline growth rate is assigned a green color. The topic region with a higher (lower) growth rate is assigned a warmer (colder) color. If the topic is brand new, the region is colored red.

### Content map analysis for 1990–1999

Figure 7 shows the content map for papers from 1990 to 1999, when nanotechnology research was already a rapidly developing domain. More frequent paper topics covered each by thousands of papers are

- research tools (e.g., “Scanning Tunneling Microscopes,” “Transmission Electron Microscopy,” “Atomic Force Microscope”);
- physical phenomena (e.g., “Quantum Dots,” “Single Crystals,” “Self-Assembled Monolayers,”

**Table 9** Top 20 countries/regions with more than 200 papers (1976–2004) based on the average number of cites by Dec. 2004

Rank	Country/Region	No. of papers	Average no. of cites
1	Switzerland	4,280	18.33
2	USA	61,068	15.46
3	Hong Kong	260	14.38
4	Netherlands	3,635	14.12
5	Denmark	1,525	13.99
6	Israel	2,509	13.02
7	England	10,394	12.30
8	Canada	5,017	12.04
9	Germany	21,334	11.35
10	France	13,777	10.61
11	New Zealand	353	10.33
12	Belgium	2,409	10.31
13	Scotland	1,035	10.28
14	Sweden	3,062	10.03
15	Austria	1,732	9.45
16	Norway	367	9.39
17	Australia	2,788	9.35
18	Italy	6,879	8.62
19	Ireland	710	8.28
20	Finland	1,201	8.04

- “Nanomolar Concentrations,” “Porous Silicon,” “Surface Morphologies”); and
- experiment environments (e.g., “Electric Fields,” “X-Ray Diffraction,” “Temperature Dependences,” “Activation Energies”).

### Content map analysis for 2000–2004

Figure 8 shows the content map of nanotechnology papers published between 2000 and 2004. It also visualizes the topic growth rates in different colors. Table 12 compares the topics of the two time periods shown in the content maps. In the table, some regions’ paper numbers are listed as “NS (Not Shown).” These topics appeared in only one of the content maps and had too few papers in the other time period to be reported by the content map. Table 12 arranges topics in three sections according to the appearance of the topics in the two time periods’ content maps. We observe that the research in the two

time periods shares several topics, which are related to research tools (e.g., “Scanning Tunneling Microscopies,” “Transmission Electron Microscopy,” “Atomic Force Microscope”), physical phenomena (e.g., “Quantum Dots,” “Self-Assembled Monolayers,” “Molecular Beam Epitaxy”), and experiment environments (e.g., “X-Ray Diffraction,” “Aqueous Solutions”). In general, the number of papers in these topics shows a pattern of growth. However, some research topics related to some specific results and experiment materials became less active, including “Single Crystals,” “Porous Silicon,” “Surface Morphologies,” etc. In addition, some topics became more active in the field during this time period, including “Carbon Nanotubes,” “Single-Walled Carbon Nanotubes,” “Heat Treatments,” “Chemical Vapor Deposition,” “X-Ray Photoelectron Spectroscopy,” “Thermal Stabilities,” and “Magnetic Fields.”

### Citation network analysis

The analysis of paper citation networks allows us to study knowledge-diffusion patterns and detect knowledge-spillover patterns at the country level and institution level. As shown in Fig. 9, after citation extraction and aggregation, we use network topological measures, including average path length, clustering coefficient, etc. (Li et al. 2007a), to infer the global characteristics of the citation networks. Then, from the country and institution citation networks we extract the core citation networks containing the top 100 papers most frequently cited between countries/institutions. The core citation networks represent the knowledge diffusion pattern in the nanotechnology domain. The core citation networks are visualized using an open source graph visualization software, Graphviz, provided by AT&T Labs (Gansner and North 2000) (available at: <http://www.research.att.com/sw/tools/graphviz/>). This tool and the resulting visualization aids in identifying knowledge diffusion patterns. The direction of the links represents the direction of the citations (i.e., a link from “Country A” to “Country B” means that Country A’s papers cited Country B’s papers) and the number beside the link represents the total number of these citations.

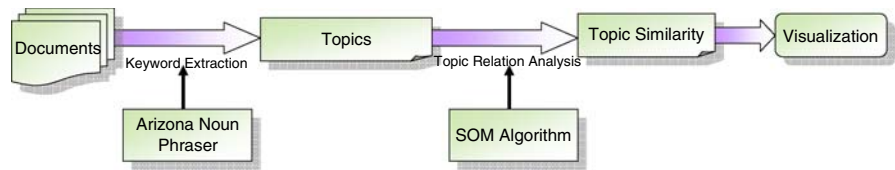
**Table 10** Top 20 institutions with more than 100 papers (1976–2004) based on the average number of cites by Dec. 2004

Rank	Institution	Country/Region	No. of papers	Average No. of cites
1	AT&T Bell Labs	USA	221	44.22
2	European Mol Biol Lab	Germany	108	42.17
3	Harvard Univ	USA	1,292	40.97
4	Inst Charles Sadron	France	113	38.79
5	Scripps Res Inst	USA	271	36.80
6	Rice Univ	USA	623	34.25
7	IBM Corp	USA	1,191	34.20
8	Univ Calif San Francisco	USA	257	33.82
9	NCI	USA	248	30.02
10	Univ Calif Santa Barbara	USA	1,322	28.83
11	Stanford Univ	USA	904	26.71
12	Max Planck Inst Biochem	USA	136	25.96
13	Colorado State Univ	USA	207	25.62
14	Lawrence Berkeley Lab	USA	172	25.38
15	Univ Strasbourg	France	431	23.83
16	Univ Calif Berkeley	USA	1,809	23.68
17	Indiana Univ	USA	231	23.66
18	Michigan State Univ	USA	461	22.91
19	MIT	USA	1,597	22.90
20	Univ Miami	USA	178	22.86

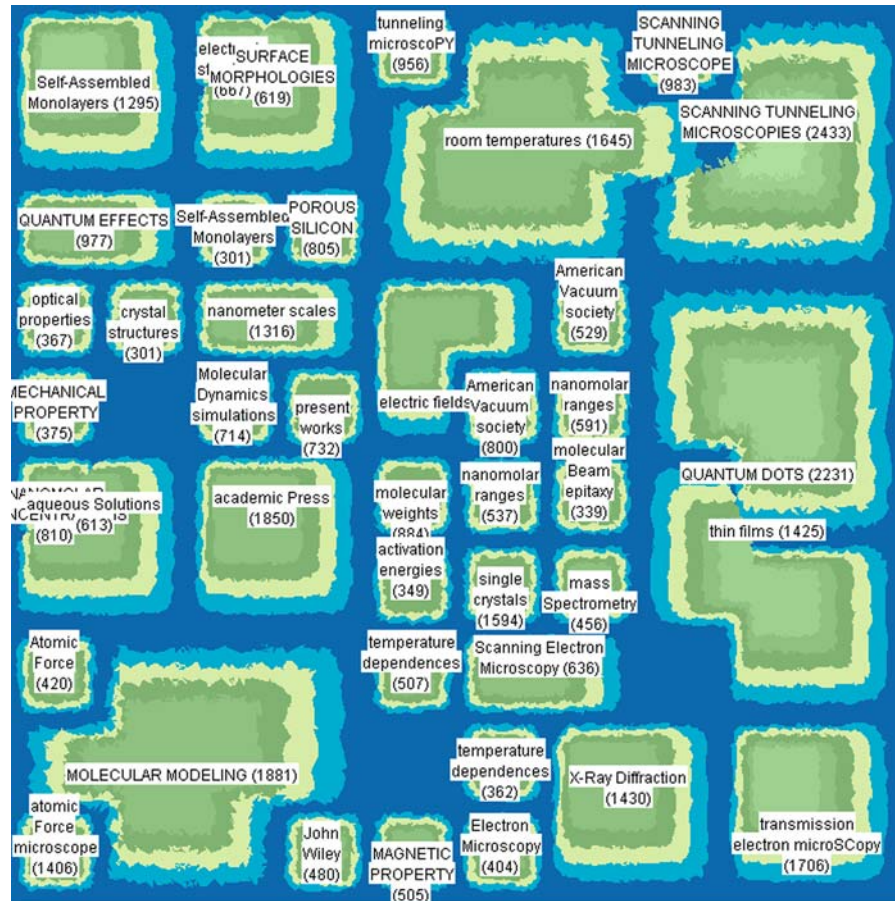
**Table 11** Top 20 journals with more than 20 papers (1976–2004) based on the average number of cites by Dec. 2004

Rank	Journal	No. of papers	Average no. of cites
1	Chem Rev	85	166.21
2	Cell	46	155.57
3	Nature	739	110.09
4	Science	1,196	109.66
5	Prog Mater Sci	23	108.57
6	Rev Mod Phys	39	102.90
7	Adv Phys	22	91.05
8	J Clin Invest	32	74.06
9	Annu Rev Phys Chem	58	68.67
10	Accounts Chem Res	118	66.03
11	Annu Rev Mater Sci	41	61.15
12	J Cell Biol	84	60.99
13	Rep Prog Phys	50	57.86
14	J Mol Graphics	65	56.49
15	Surf Sci Rep	75	55.44
16	J Chem Soc Chem Comm	98	51.73
17	Phys Rep	67	50.36
18	Embo J	94	49.98
19	Chem Soc Rev	46	49.61
20	J Phys Chem-US	624	48.47

**Fig. 6** Content map analysis process



**Fig. 7** SCI paper content map (1990–1999) for nanotechnology



We evaluated topology of the citation network for all nanotechnology literature published between 1976 and 2004. For core network analysis, we also extracted the core networks for the three time spans (i.e., 1976–1989, 1990–1999, and 2000–2004). The three core networks have been compared with each other to identify the evolution of inter-country and inter-institution knowledge diffusion.

**Country citation network**

Table 13 shows the topological measures of the country citation network for the papers published

between 1976 and 2004. The network consists of 66 countries, 348 inter-country citation relations, and 9 self-citation relations. The network contains only one component. In other words, the researchers in every country directly or indirectly affect each other through citations. The country citation network’s clustering coefficient (0.693) is much larger than that of a random network (0.162) of the same size, which indicates that countries tend to form citation communities in nanotechnology research.

Figure 10 shows a portion (due to space limitations) of the core network of the country citation network from 1976 to 2004, which contains the top 100 citation relations (i.e., links) according to the frequency that

**Fig. 8** SCI paper content map (2000–2004) for nanotechnology



citations happened. In this graph, the USA was the largest citation center (with 36 most frequent citation relations). Japan (with 23 citation relations), Germany (18), France (14), and China (10) were secondary citation centers. These major citation centers also had close citation relationships among them. We also generated three core country citation networks for 1976–1989, 1990–1999, and 2000–2004 (<http://ai.arizona.edu/research/nanomapping/ISICitationNetworks.htm>). By comparing the three core networks, we found that:

- From 1976 to 1989, few citations are noted among nanotechnology papers. The USA and Japan have more citations than other countries.
- From 1990 to 1999, a large number of citations appear. The USA became a major citation center, with Japan, Germany, China, France, England, and Russia following. Close citation relationships emerge among these major countries.

- From 2000 to 2004, in addition to the major citation centers of the 1990s, South Korea also emerges as an important citation center. The USA, Germany, Japan, and France become the kernels of different research communities. They share close citations with different groups of secondary countries in nanotechnology research.

### Institution citation network

The institution citation network of papers published between 1976 and 2004 consists of 1,237 institutions, 3,075 inter-institution citation relations, and 7 self-citation relations. As listed in Table 13, the institution citation network consists of 20 disconnected components. The largest component contains 1,185 (95.8%) institutions and 3,041 (98.9%) relations. Thus, most institutions working in the

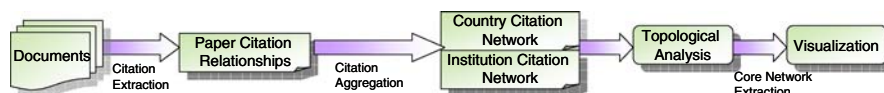
**Table 12** Topic of nanotechnology papers extracted by the SOM algorithm in 1990–1999 and 2000–2004

Region label	No. of papers in the region, 1990–1999	No. of papers in the region, 2000–2004	Growth rate
Heat Treatments	Not shown on the content map (NS)	2,724	N/A*
Chemical Vapor Deposition	NS	2,675	N/A
Optical Society	NS	2,580	N/A
Magnetic Fields	NS	2,451	N/A
Surface Areas	NS	2,019	N/A
Carbon Nanotubes	NS	1,931	N/A
Single-Walled Carbon Nanotubes	NS	1,863	N/A
X-Ray Photoelectron Spectroscopy	NS	1,824	N/A
Grain Boundary	NS	1,358	N/A
Thermal Stabilities	NS	836	N/A
Wiley Periodicals	NS	677	N/A
Optical Properties	367	2,477	5.75
Crystal Structures	301	1,546	4.14
Aqueous Solutions	613	3,018	3.92
Molecular Beam Epitaxy	339	1,457	3.30
Molecular Dynamics Simulations	714	2,634	2.69
Temperature Dependences	869	2,646	2.04
Molecular Weights	884	2,572	1.91
Quantum Effects	977	2,757	1.82
X-Ray Diffraction	1,430	3,965	1.77
Thin Films	1,425	3,478	1.44
Scanning Electron Microscopy	636	1,503	1.36
Magnetic Property	505	1,128	1.23
Transmission Electron Microscopy	1,706	3,720	1.18
Mass Spectrometry	456	926	1.03
Electron Microscopy	404	778	0.93
Atomic Force	420	707	0.68
Self-Assembled Monolayers	1,596	2,358	0.48
Scanning Tunneling Microscopies	3,416	4,363	0.28
Atomic Force microscope	1,406	1,759	0.25
Present Works	732	843	0.15
Electronic Structures	667	649	−0.03
Quantum Dots	2,231	2,001	−0.10
Molecular Modeling	1,881	1,420	−0.25
Electric Fields	3,625	1,004	−0.72
Activation Energies	349	NS	N/A
Mechanical Property	375	NS	N/A
Surface Morphologies	619	NS	N/A
Porous Silicon	805	NS	N/A
Nanomolar Concentrations	810	NS	N/A
Tunneling Microscopy	956	NS	N/A
Nanomolar Ranges	1,128	NS	N/A
Nanometer Scales	1,316	NS	N/A
American Vacuum Society	1,329	NS	N/A

**Table 12** continued

Region label	No. of papers in the region, 1990–1999	No. of papers in the region, 2000–2004	Growth rate
Single Crystals	1,594	NS	N/A
Room Temperatures	1,645	NS	N/A
Academic Press	1,850	NS	N/A
<i>Baseline Growth Rate</i>			0.729

\* The growth rates shown with “N/A” do not mean the topics appeared or disappeared suddenly. Since the SOM algorithm pick the active topics in a competitive fashion, the topics with a smaller number of papers will be merged with other topics and will not be shown on the content map. In such circumstance, the growth rate is not applicable

**Fig. 9** Steps in citation network analysis

nanotechnology field interact with others directly or indirectly through citation relations. Similar to the country citation network, the institution citation network also has a much larger clustering coefficient (0.069) than the random network (0.004) of the same size, which indicates that research institutions in the nanotechnology field have a strong tendency to form citation clusters. Different from the country citation network, the institution citation network has a smaller average path length (4.050) than a random network (4.440) of the same size. Such a small-world characteristic means that knowledge transfers between institutions more easily in this network than in a random network.

Figure 11 shows a portion (due to space limitations) of the core institution citation network of 1976–2004.

In this network, “University of Houston,” “Baylor College of Medicine,” and “Triplex Pharmaceutical Corporation” were the largest citation centers and created a citation cluster. “Moscow Mv Lomonosov State University” and “Eindhoven University of Technology” were also large citation centers and created another citation cluster. The core institution citation networks for the three time periods (1976–1989, 1990–1999, and 2000–2004) can be seen at <http://ai.arizona.edu/research/nanomapping/ISICitationNetworks.htm>. From these networks, we observe that:

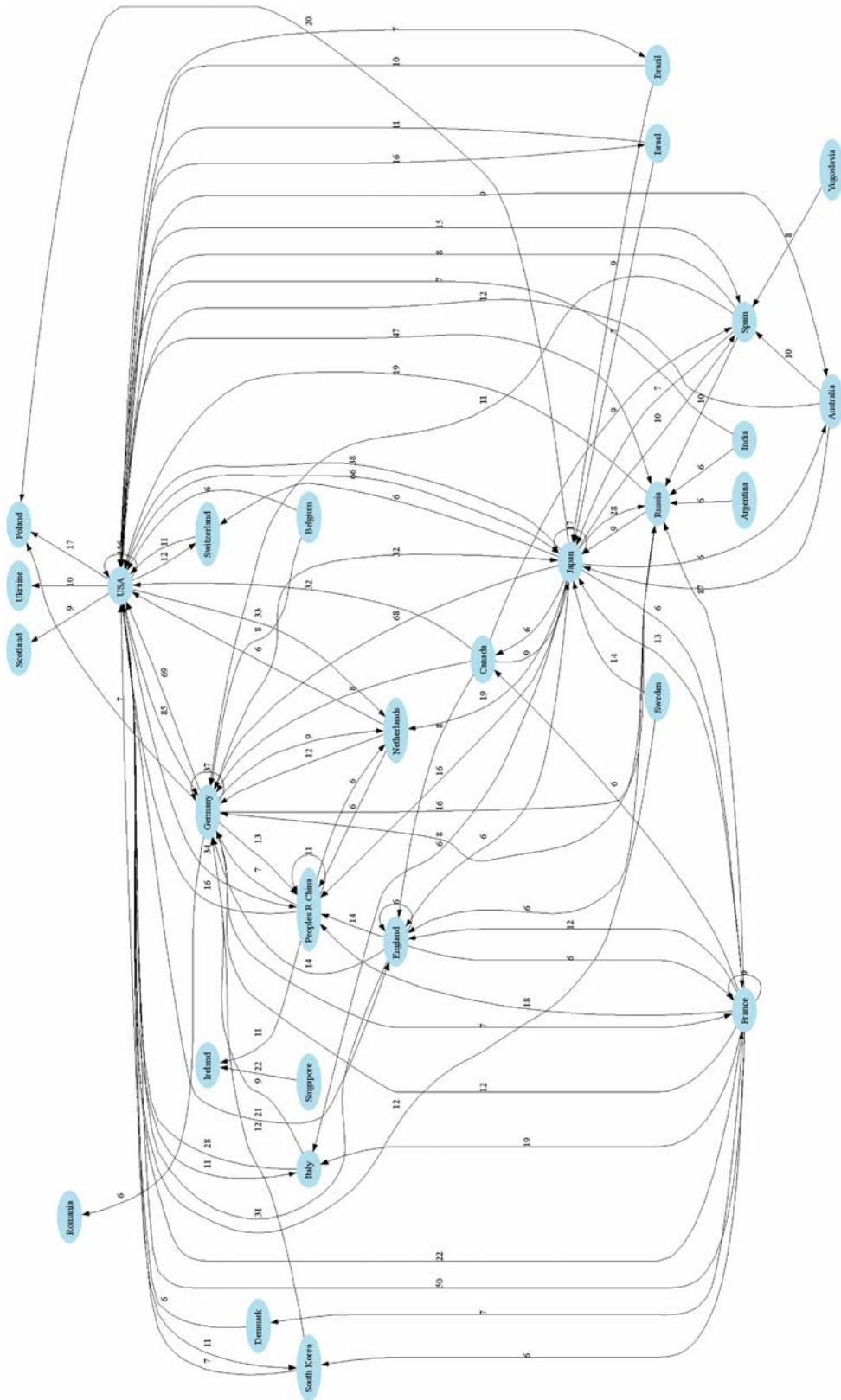
- From 1976 to 1989, very sparse citations existed between institutions. “Pfizer Inc” and “GE” were the two largest citation centers at that time.

**Table 13** Topological attributes of the country citation network and institution citation network (1976–2004)

Measures	Country citation network	Institution citation network
$l$ : average path length <sup>a</sup>	2.019	4.050
$l_{\text{rand}}$ : average path length of a random network	1.779	4.440
$C$ : clustering coefficient <sup>b</sup>	0.693	0.069
$C_{\text{rand}}$ : clustering coefficient of a random network	0.162	0.004
$D$ : network diameter <sup>c</sup>	4	11
$N_C$ : number of components <sup>d</sup>	1	20
$Node_C$ : number of nodes in the largest component	66 (100%)	1,185 (95.8%)
$Link_C$ : number of links in the largest component	348 (100%)	3,041 (98.9%)

<sup>a</sup> Average path length means the average value of the shortest path length between any pair of nodes in the network. A short average path length means that knowledge will move to different parts of the graph more quickly; <sup>b</sup> The network’s clustering coefficient is the average of each node’s clustering coefficient, which is the ratio of the number of edges between the node’s neighbors to the number of possible edges between those neighbors. The clustering coefficient indicates the tendency for the analytical units to form local clusters; <sup>c</sup> Network diameter is the maximum value of the shortest path length between any pair of nodes in the network. <sup>d</sup> A component is an isolated sub-network in a disconnected network





**Fig. 10** Portion of the SCI nanotechnology paper country citation network (1976–2004)

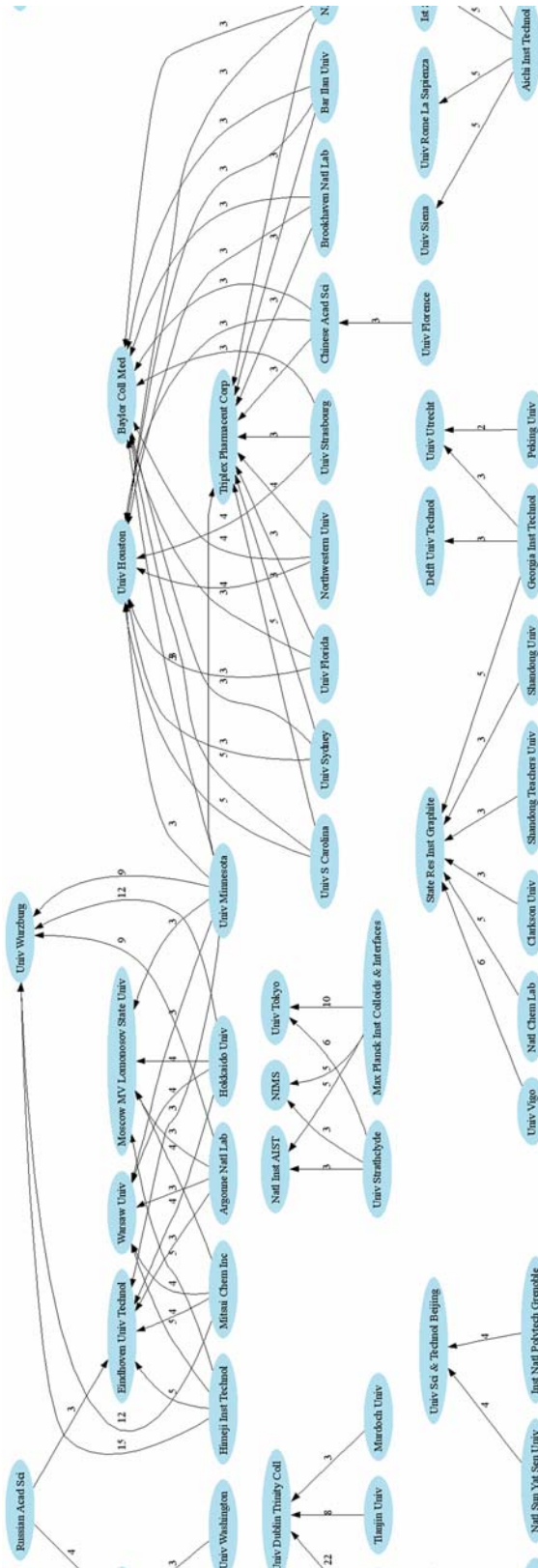


Fig. 11 Portion of the SCI nanotechnology paper core institution citation network (1976–2004)

- From 1990 to 1999, institution level research clusters emerged. “University of Houston (U.S.),” “Baylor College of Medicine (U.S.),” “Triplex Pharmaceutical Corporation (U.S.),” and “State Research Institute of Graphite (Russia)” were the major citation centers of the largest two citation clusters. Many of the major citation centers in this network are USA institutions.
- From 2000 to 2004, many citation clusters formed. The largest citation cluster included “Moscow Mv Lomonosov State University,” “Warsaw University,” “University of Wurzburg,” and “Eindhoven University of Technology.” Some of the smaller citation clusters, including the ones around “University of Tokyo” and “University of Science & Technology Beijing,” had indirect connections with this citation cluster and created a citation cluster. Many of the citation centers in this network were from various countries in Europe and Asia.

## Conclusions

After identifying the nanotechnology papers documented in the SCI database by keywords for the interval 1976–2004, we conducted a longitudinal research study using bibliographic analysis, content map analysis, and citation network analysis. On this basis, nanotechnology development status reflected in publications has been evaluated at different levels, including author, country, institution, etc. Key findings are:

- There was a quasi-exponential growth pattern in nanotechnology paper publication after 1991 with an annual rate of 20.7%. Most of the top countries, institutions, and journals consistently exhibited such rapid growth after 1991.
- The United States dominated the number of nanotechnology paper publication in the 1976–2004 interval. China (second in 2004) and South Korea (sixth in 2004) have showed rapid growth in nanotechnology research after the second half of the 1990 s. Japan, Germany and France have maintained their relative ranking in the top five countries in this time interval.
- The institutions with the largest numbers of published papers are the Chinese Academy of Sciences and Russian Academy of Sciences, followed by a more compact group lead by the University of Tokyo, CNRS and University of Paris.
- The United States led the indicators based on the average number of cites by December 2004 per paper published between 1976 and 2004 for both:
  - (a) key researchers (16 of the top 20 researchers were from the U.S., followed by France with two, and Germany and Netherlands with one each) and
  - (b) key institutions (17 of 20 top institutions were from the U.S., followed by France with two and Germany with one). The most cited institutions in nanotechnology by December 2004 were AT&T Bell Labs, European Molecular Biology Laboratory, and Harvard University.
- The top five countries/regions based on the number of average citations per paper by December 2004 were Switzerland, U.S., Hong Kong, Netherlands, and Denmark.
- The more frequent citations were on research papers dealing with tools, theories, technologies, perspectives, and overviews of nanotechnology, and were published in journals which are generally highly recognized in academia.
- The content map analysis identified a broad range of topics related to tools, physical phenomena, and experiment environments in nanotechnology research, and the increasing of new topics in 2000–2004, such as “Carbon Nanotubes,” “Chemical Vapor Deposition,” “X-Ray Photoelectron Spectroscopy,” and “Thermal Stabilities.”
- The network topological analysis shows the relatively high clustering coefficients of both the country citation network and the institution citation network from 1976 to 2004, indicating the existence of citation communities in the two networks.
- The USA, Japan, Germany, France, and China were major citation centers in nanotechnology citation networks. There were close citation relationships exist among these centers.
- The “University of Houston,” “Baylor College of Medicine,” and “Triplex Pharmaceutical

Corporation” were the largest citation centers and composed a large citation cluster.

In future work, we plan to investigate the evolution of co-authorship and respective collaborations in the nanotechnology papers from the SCI database. It is expected that combining co-authorship and citation network analyses will lead to a more comprehensive understanding of the knowledge exchange and diffusion patterns between nanotechnology researchers, institutions, and countries.

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