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Global nanotechnology research metrics

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Text mining was used to extract technical intelligence from the open source global nanotechnology and nanoscience research literature. An extensive nanotechnology/nanoscience-focused query was applied to the Science Citation Index/Social Science Citation Index (SCI/SSCI) databases. The nanotechnology/nanoscience research literature infrastructure (prolific authors, key journals/institutions/countries, most cited authors/journals/documents) was obtained using bibliometrics. A novel addition was the use of institution and country auto-correlation maps to show co-publishing networks among institutions and among countries, and the use of institution-phrase and country-phrase cross-correlation maps to show institution networks and country networks based on use of common terminology (proxy for common interests). The use of factor matrices quantified further the strength of the linkages among institutions and among countries, and validated the co-publishing networks shown graphically on the maps.

Background

Due to the exponential growth of the open nanotechnology literature, there is need for gaining an integrated quantitative perspective on the state of this literature.

The views in this paper are solely those of the authors, and do not represent the views of the Department of the Navy or any of its components, or the Institute for Defense Analyses

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In 2003–2005, a comprehensive text mining study was performed to overview the technical structure and infrastructure of the global nanotechnology research literature, as well as the seminal nanotechnology literature (KOSTOFF et al., 2005a, 2005b, 2006a, 2006b). Based on the global interest generated by these reports, it was decided to update and expand the study using more recent data, a much more comprehensive query, and more sophisticated analytical tools. The present paper represents the scientometric component of the updated and expanded study. A more detailed report on the updated study's results and methodologies is contained in KOSTOFF et al., 2007. Finally, since a comprehensive background of the seminal works in nanotechnology is contained in (KOSTOFF et al., 2005b, 2006b), it will not be repeated here.

Introduction

Broadly speaking, nanotechnology is the development and use of techniques to study physical phenomena and to construct structures in the physical size range of 1–100 nanometers (nm), as well as to incorporate these structures into applications. Although size is a convenient way of defining the area, it alone is not enough to distinguish the nanoscale material from microscopic material. For example, there is no line of demarcation that separates structures at 120 nm from those of 100 nm. In practice, nanotechnology has more to do with the investigation of novel properties that manifest themselves at that size scale, and of the ability to manipulate and artifically construct structures at that scale. Experiments and computer simulation have been targeted at materials and structures in these very small scales for decades. The advances in high speed and high storage capacity computers, as well as accurate instruments for measuring and manipulating at the nanoscale, have accelerated the development of nanoscale structures and devices into reality.

Along with the growth in the tools and products of nano-science and technology has come the growth in the related technical literature. Publications in the Science Citation Index/Social Sciences Citation Index (SCI/SSCI) (SCI, 2006) grew from 11,265 articles in 1991 to 64,737 articles in 2005 (almost a sixfold increase in fourteen years) using the ~300 term query developed for the present study.

Given this voluminous literature, as well as the other voluminous literatures of Patents, Technical Reports, other large databases, and the Web, how can one gain an integrated perspective of the overall state of nanotechnology? Text mining offers one potential approach. This paper describes the results of applying one component of text mining (evaluative bibliometrics) to the SCI and SSCI nanotechnology literature.

Approach

Databases

The primary objective of this study was to identify and analyze the global research literature that was related directly to nanotechnology/nanoscience. Because citation bibliometrics are an important tool used by the first author's text mining group, and this citation capability is an SCI/SSCI specialty, the SCI/SSCI was selected as the database for the analyses. Additionally, it was desired to focus on the original research component of the SCI/SSCI, as well as reviews, and not mix objects of different categories (e.g., editorials, letters, etc.). Therefore, only records classified as Articles or Reviews in the SCI/SSCI were downloaded into the dataset for analysis.

The SCI/SSCI-retrieved database consisted of selected journal records (including authors, titles, journals, author addresses, author keywords, abstract narratives, and references cited for each paper) obtained by searching the Web version of the SCI/SSCI for nanoscience/nanotechnology original research and review articles. While some time trends were studied, most of the analysis covered 2005 only.

Query development

Once the source database was selected, a comprehensive query was developed. The query has three components and about 300 terms (KOSTOFF et al., 2007). The first component was generated using an iterative relevance feedback technique (KOSTOFF et al., 1997) applied to the phrases in the Abstract fields of the SCI/SSCI records. The second component consists of journals that contain 'nano*' in their titles (* is the wild card character typically used in database searches), and the third component consists essentially of addresses that contain 'nano*'. The retrievals from each query component have been validated for relevance and precision.

Bibliometrics

Bibliometrics is a method for quantitative analysis and statistics. It is used to describe patterns of publication in nanotechnology/nanoscience. The results from the publications bibliometric analyses are presented first, followed by the results from the citations bibliometrics analyses. The publications bibliometrics are counts of papers published by different entities, and can be viewed as output and productivity measures. The citation bibliometrics are counts of citations to documents published by different entities. The citations in all the retrieved SCI/SSCI papers were aggregated, the authors and journals cited most frequently were identified, and are presented in order of decreasing frequency.

Factor analysis

Factor analysis of a text database is a method to reduce the number of variables in a system by grouping them, and to detect structure in the relationships among variables. Correlations among variables are computed, and highly correlated groups (called factors) are identified. The relationships of these variables to the resultant factors are displayed in the factor matrix, whose rows are variables and columns are factors. In the factor matrix, the matrix elements M_{ij} are the factor loadings, or the contribution of variable i (in row i) to the theme of factor j (in column j). The theme of each factor is determined by those variables that have the largest values of factor loading. Each factor has a positive value tail and negative value tail. For each factor, one of the tails typically dominates in terms of absolute value magnitude. This dominant tail is used to determine the central theme of each factor. Factor analysis was used to quantify inter-institution and inter-country collaborations.

Correlation mapping

An auto-correlation function describes the correlation between a function and a copy of itself shifted by some 'lag' distance. One can produce a correlation map showing terms that commonly occur together over a period of time. For example, strong linkages in the auto-correlation map of institutions show teams of institutions that publish together.

A cross-correlation map shows relationships among items in a list based on the values in another list. Similarly, strong linkages in the cross-correlation map of institutions and phrases can show groups of organizations that write about the same things. A cross-correlation map of countries and phrases can show groups of nations that write about the same things.

Results

Publication time trends

Numbers of aggregate publications. Figure 1 shows the annual totals of nanotechnology/nanoscience articles retrieved from the SCI/SSCI for the period 1991–2005. The points are the actual number of articles retrieved, the solid line is an exponential fit to the data that includes the two end points, and the two dotted lines are linear fits to the data for adjacent time periods (1991–2000; 2001–2005). The slope of the second line is greater, indicating that the rate of increase of nanoscience/nanotechnology articles produced was higher in the last five years than during the 1990s.

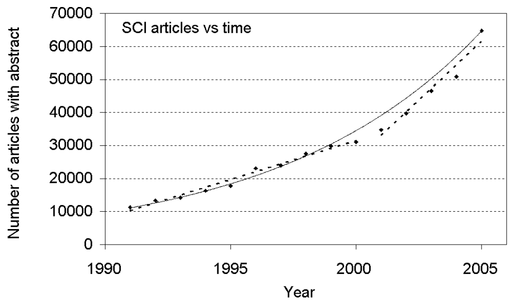

Figure 1. SCI/SSCI articles vs time. Total records retrieved

Temporal country publication distributions. Figure 2a shows the breakdown of nanoscience/nanotechnology article production by country for three selected years (1991, 1998, and 2005). All of the leading countries in nanotechnology have increased production from 1991 to 2005, but the growth in research has not been uniform globally. The USA leads the world in nanotechnology paper publications, whereas the most dramatic increase is from the Peoples Republic of China, from 1,860 papers in 1998 to 11,768 papers in 2005.

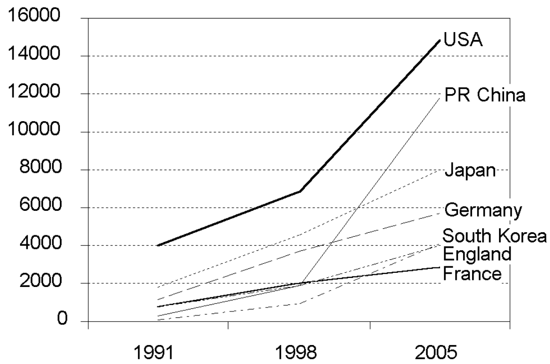

Figure 2a. Country comparison time trend

Figure 2b shows the breakdown of nanoscience/nanotechnology article production by countries in percentage shares for the same three selected years. The numbers in parentheses above the bars are actual numbers of papers produced for the year in question. Over this time period, the United States' and Japan's shares of global nanotechnology/nanoscience publications have dropped (the USA dropped from 36% to 23%, and Japan from 16.5% to 12.5%), as countries that were not as prolific at the beginning of the 1990s grew rapidly over the course of the decade. Most notably, China and South Korea both published about forty times more research articles in 2005 than in 1991. The other leading countries increased their output by at most five times.

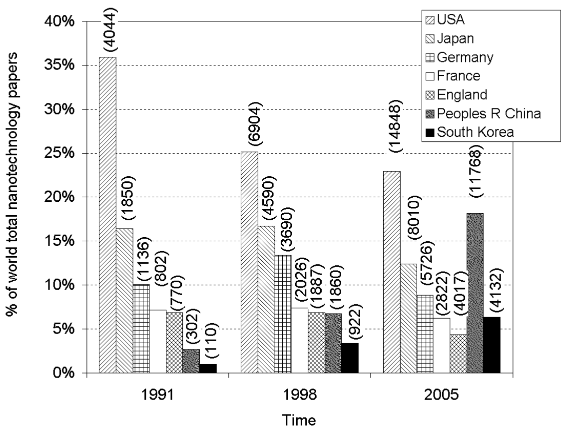

Figure 2b. Country time trend percentages

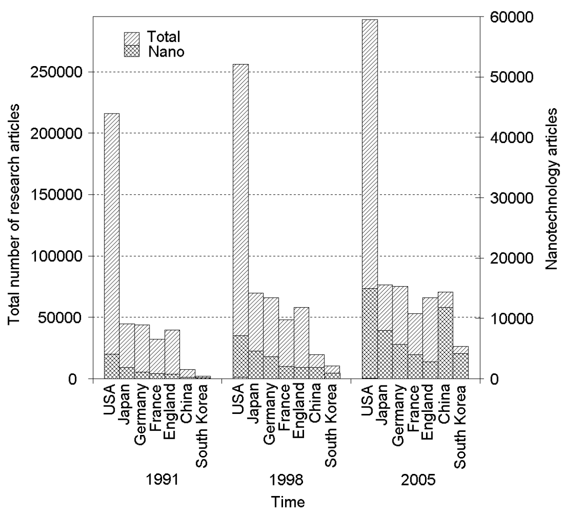

Figure 2c. Nanotechnology articles and total articles

Figure 2c places these nanotechnology/nanoscience numbers in perspective by plotting their temporal trends as a function of total country SCI/SSCI articles. As the total number of research articles for most countries has gone up, the percentage of nanotechnology papers has also gone up disproportionately relative to other technical disciplines.

From the aggregate country temporal perspective of Figure 2b, the US appears well ahead of China in numbers of articles produced, although China is growing rapidly. From the aggregate nanotechnology perspective of Figure 2a, the US is moderately ahead of China in articles produced, although China appears poised to overtake the US in a few years if the trends shown continue.

Temporal nanotechnology sub-area publication distributions across countries. While the publication results aggregated across all nanotechnology/nanoscience sub-areas are interesting, even more illuminating are the results dis-aggregated by nanotechnology sub-area. Based on a recent comparison of China's research area emphases with those of the US (KOSTOFF et al., 2006c), some nanotechnology sub-areas were identified where China's research article outputs were comparable in absolute numbers to those of the US. The time histories of the major country contributors to three selected nanotechnology sub-areas are shown in Figures 3a-3c.

Two caveats are in order. The numbers shown do not add up to 100% in any year, since only four selected countries are shown. Other contributors will supply the remainder. Second, when all contributions are included, the numbers could total beyond 100%, since co-authored papers are counted for each of the co-authors. With those caveats, the discussion proceeds.

Figure 3a shows that the U.S. percentage of "XRD and nano*" has gone down substantially from 67% in 1991 down to 8% in 2005, whereas China's share has gone up from 30% in 1994 up to 52% in 2005. Figure 3b shows a similar trend in nanocomposites, where the U.S. share went down from 44% in 1991 to 23% in 2005 and China's share went up from 4% in 1994 to 24% in 2005. Again, similar trend is shown in Figure 3c in the sub-area of nanocrystals. The U.S. share went from 27.5% in 1991 down to 21% in 2005, and China's share went from 4.4% in 1991 up to 24% in 2005.

From the dis-aggregated nanotechnology perspective of Figures 3a–3c, China has already achieved parity with the US in some important nanotechnology sub-areas, at least from an article production perspective. This analysis shows the importance of going beyond the national aggregate (overall technology) level, as exemplified by KING (2004), and even beyond a broad technology aggregate level (such as nanotechnology), to understand critical sub-technology trends occurring globally.

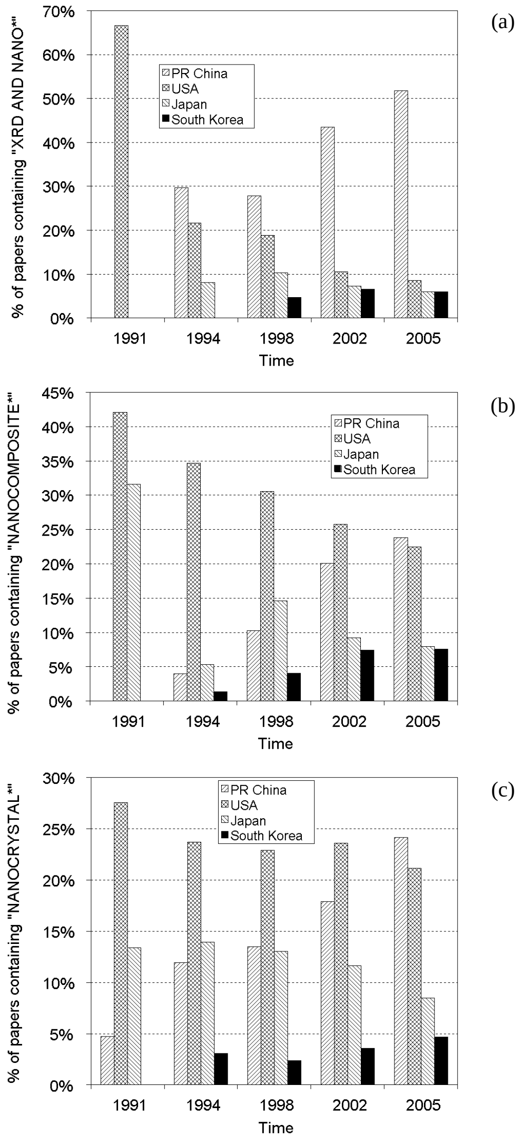

Figure 3. Number of papers containing (a) "XRD and nano*"; (b) "nanocomposite*"; (c) "nanocrystal*"

Bibliometrics

Prolific authors

1. List of prolific author names (names appear anywhere in author field).

Table 1 presents the 30 most prolific nanotechnology research author names from 2005 and their publication frequency. All of the names listed are monosyllabic, either of Chinese or Korean origin, and many surnames are identical. This implies that the names are quite common, and for a field of study as large as nanoscience/nanotechnology one might easily find multiple authors with the same name. The unrealistically high (by historical and Western standards) author publication frequencies listed for one year lends credibility to that assumption.

Table 1. Most prolific nanotechnology research author names (2005)*

Author	Number of papers
Zhang, Y	237
Wang, J	219
Li, Y	215
Wang, Y	209
Liu, Y	204
Zhang, J	174
Lee, JH	165
Wang, L	151
Kim, JH	142
Chen, Y	141
Wang, X	139
Li, J	137
Zhang, L	137
Wang, H	135
Kim, J	133
Kim, SH	115
Lee, J	114
Lee, JY	113
Lee, S	111
Liu, J	111
Chen, J	107
Xu, J	106
Yang, Y	104
Li, L	103
Zhang, X	102
Wang, Q	98
Kim, H	92
Lee, SJ	90
Yang, J	87
Zhang, H	87

* Note: Each name does not necessarily refer to one person.

2. List of prolific authors and their institutions (names disambiguated)

To dis-ambiguate the author names, an author-institution co-occurrence matrix is generated for the most prolific authors and institutions. The top authors are extracted manually, by looking for author-institution pairings with high publication totals. This method identifies each author uniquely provided that each institution contains only one author with a given full name in a specific technology. However, the software is not configured to allow mapping by authors deconvolved using this approach.

Only four names from the list of top 30 prolific author names (Table 1) remained in the list of the 29 most prolific authors (Table 2). The author with the most papers, Qian, YT in Table 2 with 86 papers fell below the threshold of 87 papers in the list of 30 in Table 1. The four authors included in both tables are Zhang, Y (45/237), Li, Y (54/215), Liu, Y (43/204), and Zhang, J (39/174), given here with the amount of papers they published and the total amount of papers for authors with the same name. The top 29 authors are dominated by Chinese authors, as were the names, but other nations are represented, and there is a smaller Korean presence. Work continues on improving the name dis-ambiguation procedure, and will be reported in *Scientometrics* at a later date.

Table 2. Most prolific nanotechnology research authors listed with their institution (2005)

Author	Number of papers	Institution	Country
Qian, YT	86	UNIV SCI & TECHNOL CHINA	Peoples R China
Li, Y	54	CHINESE ACAD SCI	Peoples R China
Jiang, L	53	CHINESE ACAD SCI	Peoples R China
Chu, PK	52	CITY UNIV HONG KONG	Peoples R China
Cingolani, R	52	UNIV LECCE	Italy
Zhang, LD	52	CHINESE ACAD SCI	Peoples R China
Wang, ZG	51	CHINESE ACAD SCI	Peoples R China
Zhang, Y	45	CHINESE ACAD SCI	Peoples R China
Du, YW	44	NANJING UNIV	Peoples R China
Hopkinson, M	44	UNIV SHEFFIELD	England
Shi, JL	44	CHINESE ACAD SCI	Peoples R China
Gao, L	43	CHINESE ACAD SCI	Peoples R China
Liu, Y	43	CHINESE ACAD SCI	Peoples R China
Knoll, W	42	MAX PLANCK INST POLYMER RES	Germany
Zhu, DB	42	CHINESE ACAD SCI	Peoples R China
Chang, SJ	41	NATL CHENG KUNG UNIV	Taiwan
Mullen, K	41	MAX PLANCK INST POLYMER RES	Germany
Bando, Y	40	NATL INST MAT SCI	Japan
Bhushan, B	40	OHIO STATE UNIV	USA
Lee, ST	40	CITY UNIV HONG KONG	Peoples R China
Reinhoudt, DN	40	UNIV TWENTE	Netherlands
Schubert, US	40	EINDHOVEN UNIV TECHNOL	Netherlands
Yu, DP	40	PEKING UNIV	Peoples R China
Arakawa, Y	39	UNIV TOKYO	Japan
Kim, TW	39	HANYANG UNIV	South Korea
Li, YD	39	TSING HUA UNIV	Peoples R China
Zhang, J	39	CHINESE ACAD SCI	Peoples R China
Liu, WM	38	CHINESE ACAD SCI	Peoples R China
Pearton, SJ	38	UNIV FLORIDA	USA

Prolific journals

The journals containing the most research articles on nanotechnology/nanoscience are shown in Table 3. The highest ranking journals, based on the number of papers, emphasize physics, chemistry, and materials, in that order. The physics journals listed have a median Impact Factor of 3.14, the chemistry journals 4.03, and the materials journals 1.65. The two journals with nano in the titles have a combined Impact Factor of 6.42.

Table 3. Journals containing most articles on nanotechnology (2005)

Journal	Number of papers	Impact factor	Theme
Applied Physics Letters	2332	4.13	PHYS
Physical Review B	2273	3.19	PHYS
Journal of Applied Physics	1488	2.50	PHYS
Journal of Physical Chemistry B	1450	4.03	CHEM
Langmuir	1103	3.71	CHEM
Thin Solid Films	932	1.57	MATLS
Journal of The American Chemical Society	817	7.42	CHEM
Journal of Crystal Growth	776	1.68	MATLS
Japanese Journal of Applied Physics Part 1 – Regular Papers Brief Communications & Review Papers	771	1.10	PHYS
Physical Review Letters	721	7.50	PHYS
Chemistry of Materials	655	4.82	CHEM
Nanotechnology	655	2.99	NANO
Applied Surface Science	640	1.26	MATLS
Polymer	552	2.85	MATLS
Materials Letters	531	1.30	MATLS
Macromolecules	516	4.02	CHEM
Nano Letters	473	9.85	NANO
Journal of Magnetism and Magnetic Materials	456	0.99	MATLS
Surface & Coatings Technology	449	1.65	MATLS
Physica E – Low-Dimensional Systems & Nanostructures	432	0.95	PHYS
Chemical Communications	422	4.43	CHEM
Advanced Materials	409	9.11	MATLS
Chemical Physics Letters	384	2.44	PHYS
Journal of Vacuum Science & Technology B	380	1.63	PHYS
Applied Physics A – Materials Science & Processing	378	1.99	MATLS
Journal of the Electrochemical Society	376	2.19	CHEM
Surface Science	370	1.78	MATLS
Journal of Alloys and Compounds	363	1.37	MATLS
Journal of Materials Chemistry	360	3.69	MATLS
Journal of Applied Polymer Science	355	1.07	MATLS
Journal of Chemical Physics	355	3.14	PHYS

There are many causes that can contribute to low journal Impact Factor. These include low quality publications and/or limited journal circulation and/or overly applied papers and/or technical field covered (i.e., number of researchers working in technical field and available to cite papers).

Prolific institutions

1. List of prolific institutions.

Table 4 presents the 30 institutions producing the most nanotechnology research papers. Universities comprise two-thirds of the top institutions, and they account for six of the top ten. Twenty-one of the prolific institutions are located in Asia. The most prolific is the Chinese Academy of Sciences (CAS), which consists of 84 institutes throughout China, one University of Science and Technology of China at Hefei, Anhui, two colleges, four documentation centers, three technical support centers, and two news and publishing units. Both China and Japan have the largest number of prolific organizations, with eight and seven institutions, respectively. The top three institutions are not universities, but rather multi-center national research institutions. The more applied nature of such institutions correlates with the substantial representation of applied journals in Table 3.

Table 4. Institutions producing most nanotechnology papers (2005)

Institution	Country	Number of records
Chinese Acad Sci	PEOPLES R CHINA	2916
Russian Acad Sci	RUSSIA	1217
CNRS	FRANCE	824
Tsing Hua Univ	PEOPLES R CHINA	749
Tohoku Univ	JAPAN	680
Univ Tokyo	JAPAN	664
Osaka Univ	JAPAN	652
Natl Inst Adv Ind Sci & Technol	JAPAN	568
Natl Univ Singapore	SINGAPORE	565
Nanjing Univ	PEOPLES R CHINA	534
Zhejiang Univ	PEOPLES R CHINA	528
Tokyo Inst Technol	JAPAN	515
CNR	ITALY	502
Kyoto Univ	JAPAN	498
Seoul Natl Univ	S. KOREA	484
Univ Sci & Technol China	PEOPLES R CHINA	482
Univ Illinois	USA	461
Natl Inst Mat Sci	JAPAN	459
CSIC	SPAIN	455
Univ Calif Berkeley	USA	427
Univ Texas	USA	419
Peking Univ	PEOPLES R CHINA	400
Korea Adv Inst Sci & Technol	S. KOREA	392
Univ Cambridge	UK	392
Jilin Univ	PEOPLES R CHINA	378
Shanghai Jiao Tong Univ	PEOPLES R CHINA	367
MIT	USA	364
Indian Inst Technol	INDIA	361
Natl Tsing Hua Univ	TAIWAN	357
Hanyang Univ	S. KOREA	355

On the other hand, the USA institutions shown are all universities. Universities of Illinois and Texas are multi-campus state university systems, while University of California Berkeley and MIT are single campus institutions. Neither the research budgets nor numbers of researchers of the institutions are analyzed, so the relative productivity cannot be estimated and assessed at this time.

The Russian Academy of Sciences' contribution is significant because their nanoscience/nanotechnology paper output is more than half of the total nanotechnology output for the country. This indicates that the Russian Academy is the principal nanotechnology research institution in Russia, with significantly diminished participation from other universities and institutions.

2. Institution auto-correlation map.

What are the linkages among these institutions? To display linkages among institutions visually, two mapping approaches were performed: auto-correlation mapping and cross-correlation mapping. Figure 4a is an institution auto-correlation map that shows institutional relationships based on actual co-authorships. On the other hand, Figure 4b is a cross-correlation map that shows institutional relationships based on use of common terminology. Figures 4c and 4d show institutional linkages based on cited journals. The difference between the two institution-cited journal maps is that Figure 4c displays the network of institutions based on their common citation of the 500 most cited journals publishing the most nanoscience/nanotechnology articles, and Figure 4d maps institutions according to common citation of the next 500 journals. Figure 4e is a cross-correlation map of institutions and cited documents.

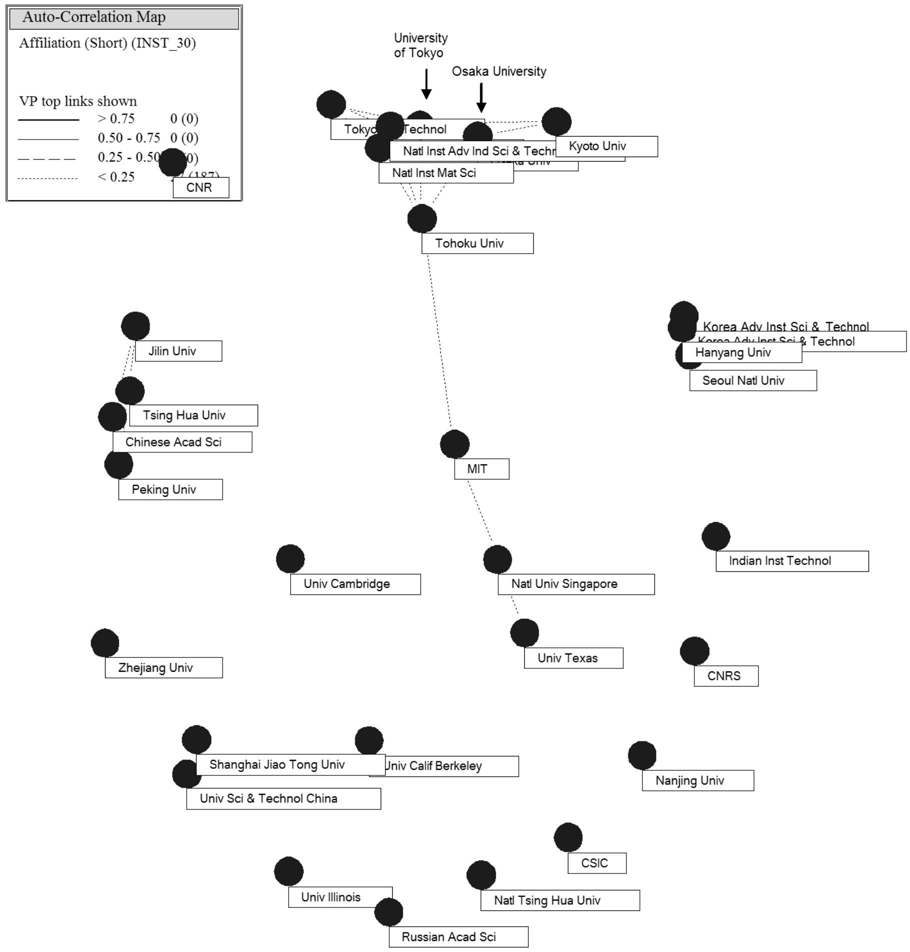

Figure 4a. Institution auto-correlation map (top thirty institutions)

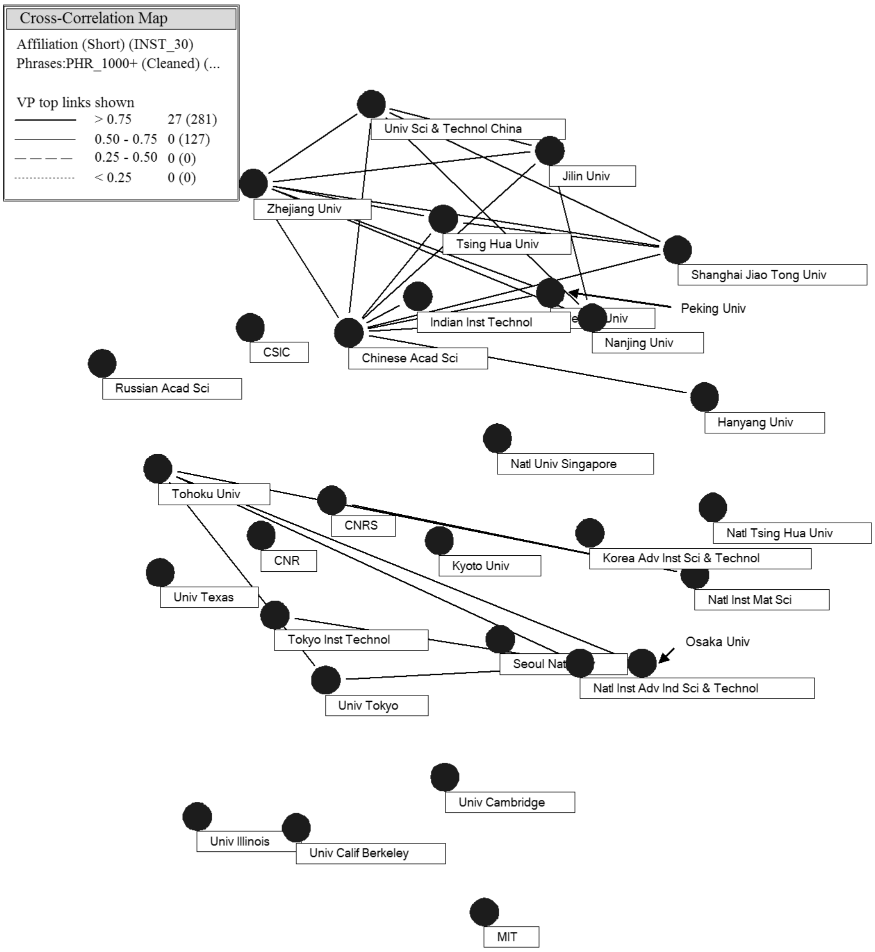

Figure 4b. Institution–phrase cross-correlation map

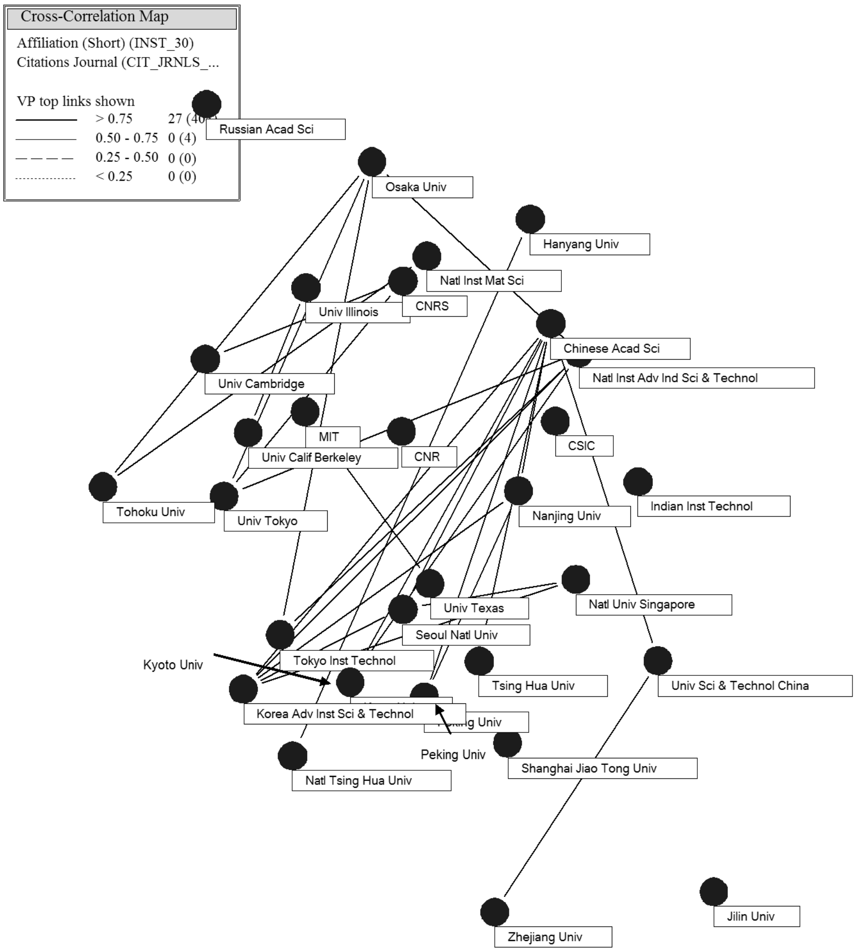

Figure 4c. Institution–cited journal cross-correlation map (cited journals 1–501)

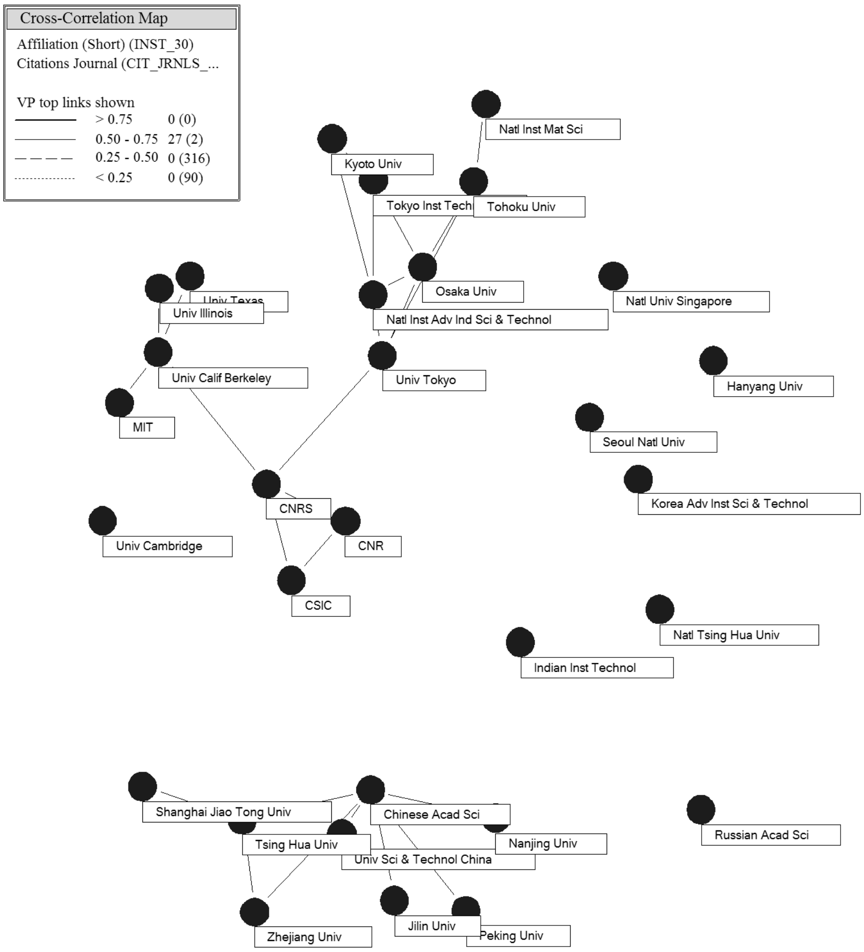

Figure 4d. Institution–cited journal cross-correlation map (cited journals 502–1003)

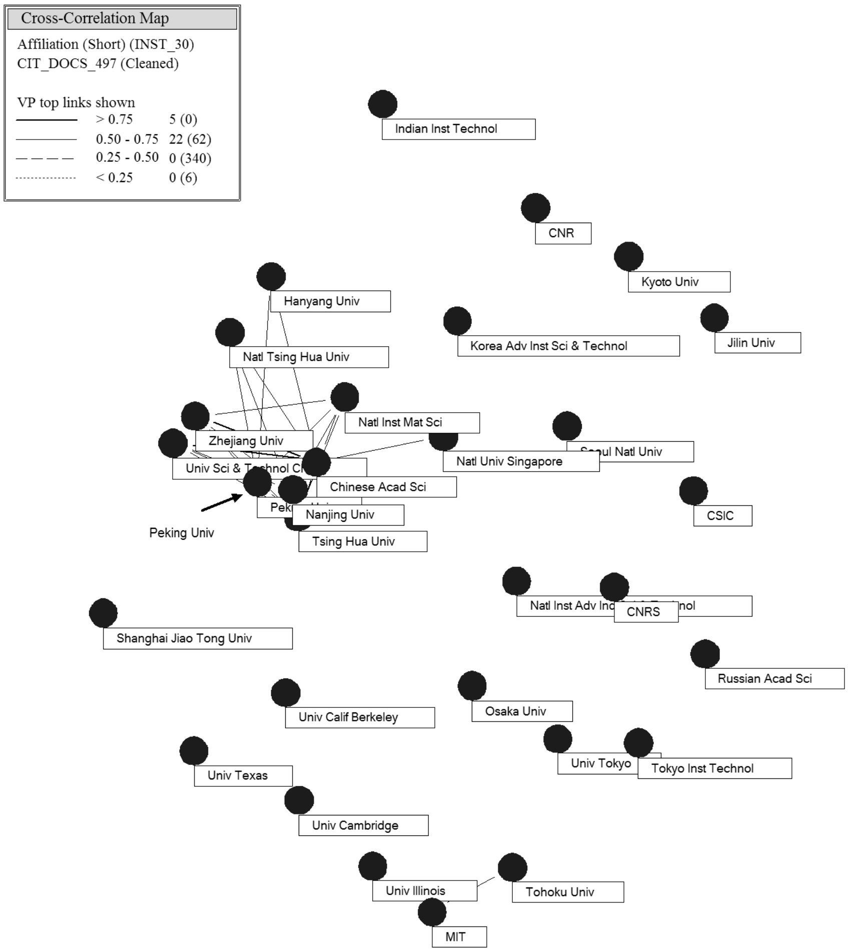

Figure 4e. Institution–cited document cross-correlation map

There are three main co-publishing groups seen in the institution auto-correlation map (Figure 4a): one Chinese, one Japanese, and one South Korean, with the Japanese group having the strongest links. All the Japanese institutions that were plotted are included in the group, namely, Tohoku University, the University of Tokyo, Osaka University, the National Institute for Advanced Industrial Science and Technology, Tokyo Institute of Technology, Kyoto University, and the National Insitute for Materials Science. Similarly, the three leading South Korean institutions (Seoul National University, Korea Advanced Institute of Science & Technology, Hanyang University) are all grouped together, but the Chinese group (Chinese Academy of

Sciences, Tsing Hua University, Peking University, Jilin University) is not all-inclusive, as a few Chinese institutions remain separate from it (Zhejiang University, Shanghai Jiao Tong Univeristy, and University Science and Technology of China). There is also weak international connectivity among MIT, the National University of Singapore, the University of Texas, and Tohoku University.

3. Institution cross-correlation maps.

Publication connectivity is much weaker than common interest connectivity or citation connectivity. On Figure 4a, all connections shown are weak (barely visible), based on the link strength criteria listed in the legend on the figure. On Figures 4b and 4c many links are very strong, and Figure 4e has strong links.

The institution–phrase cross-correlation map (Figure 4b) contains two very strongly intra-connected groups based on common thematic interest, one Chinese and one containing primarily Japanese and South Korean institutions. The Indian Institute of Technology (a national multi-institution group) forms a strong link with the Chinese Academy of Sciences as well, and CNR (Consiglio Nazionale delle Ricerche) and CNRS (Centre National de la Recherche Scientifique) are included in the Japanese/Korean group. Four American universities and the University of Cambridge stand apart as a fourth group, but the connections among these institutions are very weak at best.

Figure 4c, the first institution–cited journal cross-correlation map, shows that the connections based on the leading cited journals are very strong. It is not possible to classify the top 30 institutions based on references to the 500 most cited journals.

Performing a cross-correlation map of the top thirty institutions with the next 500 cited journals provides a much clearer picture of linkages that exist. Figure 4d shows four clusters based on nationality: one Chinese, one Japanese, one American, and one European. The map demonstrates that institutions from the same country cite the same focused journals, and these journals tend to be domestic, although not exclusively. One can verify this result by tabulating the top five cited journals (out of Cited Journals 502–1003) for each institution and identifying their origins in the SCI. For the Chinese group, half of the 34 top journals are Chinese publications. Fourteen of the 25 identified journals for Japanese institutions were published in Japan, and nine out of ten journals are domestic for the American group. The European group is slightly different in nature, as CNR and CSIC do not have any highly cited domestic journals. However, CNRS has two of three top journals printed in France, and altogether the three institutions have twelve of fifteen cited journals published within the European Union. Another point to note from Figure 4d is that the Chinese group is isolated from the other institutions, whereas the Japanese and the American institutions link to the European research centers, both through CNRS.

The institution–cited document cross-correlation map (Figure 4e) shows a strongly-linked group of Chinese institutions, which also contains the National University of Singapore and the National Tsing Hua University (Taiwan). The isolation of the Chinese institutions in Figure 4d and the strong intra-connectivity of the Chinese institutions in Figure 4e are in line with the findings of ZHOU & LEYDESDORFF (2006). They concluded that Chinese researchers cite articles in leading international journals, but non-Chinese researchers do not cite Chinese-authored articles to the same extent, especially those published in Chinese-language journals. A part of the problem, according to Zhou and Leydesdorff, is that China publishes 4,497 scientific journals, out of which only 1,506 journals are included in the China Scientific and Technical Papers and Citations Database, and only 67 journals are translated into English in the SCI database. The strong intra-Chinese institution connectivity of Figure 4E reflects strong China-China citations. MIT and Tohoku University have a formidable link based on documents cited in common, but no other organizations are connected based on cited documents.

4. Institution factor matrices.

Based on the thirty institutions shown in Table 4 and the roughly four-five groupings discerned from the auto-correlation map of Figure 4a, the six factor institution factor matrix of Table 5 was generated (using the TechOasis software (SEARCH, 2006)). The institution names listed in Table 4 constitute the first column of Table 5, and the factors are the remaining columns. Each factor represents a group of institutions that co-author significantly. The high factor loadings that determine the main collaborators are shaded darkly, and the moderate factor loadings that represent modest/weak connectivity are shaded lightly.

Six distinct groupings, based mainly on nationality, are shown, one for each factor.

Factor 1 is the Japanese-based group. National Institute for Materials Science is strongly linked to University of Tokyo, National Institute of Advanced Industrial Science & Technology, Tohoku University, and Tokyo Institute of Technology and weakly linked to Osaka Univeristy and Kyoto University. Japanese authors from the top institutions frequently co-author research articles with their counterparts at other institutions.

Factor 2 is one of the two China-based groups. Tsing Hua University is strongly linked to Chinese Academy of Sciences, Peking University, and Jilin University. As in Japan, there is ample co-publication among the researchers from China's top institutions.

Factor 3 is the Korean-based group. Hanyang University is strongly linked to Korea Advanced Institute of Science and Technology and Seoul National University. This group represents co-authorship within South Korea only; no links to North Korea are shown.

Table 5. Six factor matrix (thirty most prolific institutions)

Factor	1	2	3	4	5	6
NATL INST MAT SCI	***0.486***	0.048	0.027	–0.038	0.054	0.02
UNIV TOKYO	***0.472***	–0.029	–0.077	0.041	–0.047	–0.057
NATL INST ADV IND SCI & TECHNOL	***0.451***	–0.013	0.008	0.034	0.026	–0.06
TOHOKU UNIV	***0.438***	0.028	0.094	–0.199	0.094	0.082
TOKYO INST TECHNOL	***0.361***	0.023	0.027	0.053	–0.055	0.038
OSAKA UNIV	*0.292*	–0.136	–0.073	0.104	0.019	*–0.221*
KYOTO UNIV	*0.199*	–0.132	–0.136	0.148	–0.065	*–0.257*
TSING HUA UNIV	–0.027	***0.536***	–0.032	0.08	–0.025	–0.013
CHINESE ACAD SCI	–0.108	***0.522***	–0.005	0.083	*0.212*	–0.153
PEKING UNIV	–0.025	***0.437***	–0.034	–0.134	–0.047	–0.101
JILIN UNIV	–0.019	***0.394***	–0.102	0.147	–0.174	–0.007
HANYANG UNIV	–0.011	–0.033	***0.588***	0.049	*–0.212*	–0.07
KOREA ADV INST SCI & TECHNOL	–0.038	–0.027	***0.572***	0.064	*–0.26*	–0.061
SEOUL NATL UNIV	–0.044	–0.058	***0.398***	0.069	*–0.26*	–0.064
MIT	0.046	0.026	0.051	***–0.561***	–0.024	0.152
NATL UNIV SINGAPORE	–0.089	–0.06	–0.069	***–0.55***	–0.021	–0.168
UNIV TEXAS	–0.094	–0.068	–0.084	***–0.434***	–0.11	–0.199
UNIV SCI & TECHNOL CHINA	–0.081	–0.093	*0.217*	–0.023	***0.556***	–0.035
SHANGHAI JIAO TONG UNIV	–0.062	–0.015	*0.22*	0.033	***0.54***	–0.007
ZHEJIANG UNIV	–0.075	–0.079	–0.015	0.002	0.18	–0.113
CNRS	–0.005	–0.054	–0.045	0.07	–0.012	***0.458***
UNIV CAMBRIDGE	0.01	0.033	0.005	–0.093	–0.014	***0.429***
CSIC	–0.039	–0.066	–0.057	0.077	–0.015	***0.407***
CNR	–0.046	–0.072	–0.07	0.097	–0.019	***0.363***
UNIV CALIF BERKELEY	–0.038	–0.021	–0.05	–0.06	*–0.212*	0.013
UNIV ILLINOIS	–0.067	0.017	–0.088	–0.018	*–0.218*	–0.02
INDIAN INST TECHNOL	–0.056	–0.125	–0.078	0.048	–0.018	–0.07
RUSSIAN ACAD SCI	–0.145	*–0.271*	*–0.227*	0.166	–0.16	–0.088
NATL TSING HUA UNIV	–0.093	–0.141	–0.094	0	–0.006	–0.13
NANJING UNIV	–0.076	–0.044	–0.089	0.188	0.094	*–0.208*

Factor 4 is the only multi-national group. MIT is strongly linked to National University of Singapore (NUS) and Univeristy of Texas. As indicated by Figure 4a this group is probably based on the individual connections between the American universities and NUS, rather than an association among all three. The Singapore-MIT Alliance (SMA) was formed in 1998, joining the engineering and life sciences programs of MIT, NUS, and Nanyang Technological University (NTU). Thus, the SMA is being used to pursue joint research in nanoscience/nanotechnology, and likely a factor matrix containing fifty institutions would include NTU in a group with MIT and NUS.

Factor 5 is the second China-based group. University of Science & Technology of China (USTC) is strongly linked to Shanghai Jiao Tong University (SJTU). These two Chinese universities are likely separate from the other top institutions of their country due to some difference in the technical thrusts emphasized. Also, note that USTC and SJTU are weakly linked to the Korean group.

Factor 6 is a Western European group. CNRS is strongly linked to University of Cambridge, CSIC, and CNR. This group represents cooperation among European institutions, as a French, a Spanish, and an Italian research center are joined with a British university.

Thus, the main groupings from the auto-correlation institution map are reproduced in the first four factors in the six factor matrix. The last two factors are additional groupings that were not readily evident in the auto-correlation map.

5. Institution–journal co-occurrence matrix.

The leading five institutions (the term institution is used loosely even though the academies have many institutes) based on the number of publications are listed below along with the five journals in which they published nanotechnology articles most frequently in 2005. The journals and institutions are followed by their Impact Factors (in square brackets) and the number of articles published. An average Impact Factor is calculated for each institution as a weighted average of the five Impact Factors listed. Non-journal sources are given an Impact Factor of zero. Note that there are no U.S. institutions in this select group.

- **Chinese Academy of Sciences [2.63] 2916** (*Applied Physics Letters* [4.13] 116, *Journal of Physical Chemistry B* [4.03] 99, *Journal of Crystal Growth* [1.68] 87, *Acta Physica Sinica* [1.05] 80, *Chinese Physics Letters* [1.28] 78)
- **Russian Academy of Sciences [1.21] 1217** (*Semiconductors* [0.62] 85, *Physics of the Solid State* [0.70] 66, *Physical Review B* [3.19] 53, *Russian Chemical Bulletin* [0.59] 50, *JETP Letters* [1.45] 41)
- **Centre National de la Recherche Scientifique [3.71] 824** (*Physical Review B* [3.19] 59, *Applied Physics Letters* [4.13] 42, *Journal of Applied Physics* [2.50] 29, *Physical Review Letters* [7.50] 23, *Journal of Crystal Growth* [1.68] 19)
- **Tsing Hua University [1.03] 749** (*High-Performance Ceramics III, Pts. 1 and 2* [0.00] 49, *Rare Metal Materials and Engineering* [0.40] 32, *Physical Review B* [3.19] 21, *PRICM 5: The Fifth Pacific Rim International Conference on Advanced Materials and Processing, Pts 1-5* [0.00] 16, *Journal of Physical Chemistry B* [4.03] 14)
- **Tohoku University [2.72] 680** (*Physical Review B* [3.19] 44, *Applied Physics Letters* [4.13] 39, *Materials Transactions* [1.10] 24, *Journal of Applied Physics* [2.50] 22, *IEEE Transactions on Magnetics* [1.01] 19)

The major thrust of four of the top five research institutions is towards physics, and a large number of articles are also published in materials science. Physics journals have higher Impact Factors than those focused on materials (as shown previously), and, in both subjects, the Impact Factor drops as journals are dedicated to a narrower field. At the institution level, the average Impact Factor is low if many articles appear in non-journal sources, which is the case for Tsing Hua University.

CNRS has the highest average Impact Factor of the five insitutions, ahead of the two universities and two national academies, which are on par with each other. Incidentally, the French research center is the only institution to have all of its top journals in the top 30 most prolific nanoscience/nanotechnology journals. Tohoku University and the Chinese Academy of Sciences have three of their top five journals in the top 30, and they have the second and third highest average Impact Factors out of the top five institutions. The Russian Academy of Sciences and Tsing Hua University, fourth and fifth highest average Impact Factors respectively, each have only one of their top journals in the top 30 journals overall.

Researchers from the national academies have a substantial amount of their work published in domestic journals. Four of the Russian Academy of Sciences' top five sources (*Semiconductors*, *Physics of the Solid State*, *Russian Chemical Bulletin*, and *JETP Letters*) are printed in Russia (albeit in English). The Chinese Academy of Sciences has two top journals published on home soil (*Acta Physica Sinica* and *Chinese Physics Letters*), the first in Chinese and the latter in English.

The top three American institutions and the journals in which they publish most frequently are shown below for comparison.

- **University of Illinois System [3.99] 461** (*Applied Physics Letters* [4.13] 39, *Physical Review B* [3.19] 35, *Journal of Physical Chemistry B* [4.03] 25, *Langmuir* [3.71] 20, *Journal of Applied Physics* [2.50] 14, *Journal of the American Chemical Society* [7.42] 14)
- **University of California-Berkeley [5.87] 427** (*Nano Letters* [9.85] 37, *Applied Physics Letters* [4.13] 33, *Physical Review B* [3.19] 32, *Physical Review Letters* [7.50] 22, *Journal of Physical Chemistry B* [4.03] 22)
- **University of Texas System [4.43] 419** (*Applied Physics Letters* [4.13] 29, *Physical Review B* [3.19] 14, *Journal of Physical Chemistry B* [4.03] 14, *Journal of the American Chemical Society* [7.42] 13, *Langmuir* [3.71] 10)

The American research institutions have higher average Impact Factors than the highest average Impact Factor of the above top five institutions located outside of the United States. This suggests that the American institutions published articles in higher quality journals, even though their publication total was lower than other institutions. Also, all of the journals listed for these American institutions are included in the top 30 journals publishing in nanoscience/nanotechnology. The American universities' articles focused on fundamental science, primarily physics and chemistry, and three journals from these fields (*Applied Physics Letters*, *Physical Review B*, and *Journal of Physical Chemistry B*) appear in all the rankings of the American universities.

Prolific countries

Table 6 contains the thirty countries producing the most nanoscience/nanotechnology research papers.

The output of research articles was dominated by the United States and China, the two nations accounting for 40% of the world's production. China's rise is particularly outstanding, as in 1991 the country was the ninth-leading country in nanotechnology, contributing 2.7% of the research articles published worldwide. In 2005, the other key players were Japan, Germany, South Korea, and France. The three most prolific Western countries (U.S, Germany, and France) and the three most prolific Asian countries (China, Japan, and South Korea) published roughly the same amount of papers, about 24,000. After the six countries that stand out, three-fifths (60%) of the remaining countries are in Europe.

Table 6. Countries producing most nanoscience/nanotechnology papers (2005)

Country	Number of papers
USA	14750
Peoples R China	11746
Japan	7971
Germany	5665
South Korea	4098
France	3994
England	2786
Italy	2297
Russia	2185
Taiwan	2165
India	2103
Spain	1700
Canada	1579
Netherlands	1130
Poland	1105
Australia	1048
Singapore	1045
Switzerland	1009
Sweden	944
Brazil	932
Belgium	712
Israel	641
Austria	540
Mexico	518
Ukraine	502
Denmark	448
Finland	428
Czech Republic	421
Turkey	418
Greece	353

Where do the leading countries publish? The leading six countries are listed below along with the five journals in which they published nanoscience/nanotechnology articles most frequently in 2005. Each institution is listed with an average Impact Factor in square brackets (calculated in the same way as for the five leading institutions above). The total number of research articles, and the journals, are followed by their Impact Factors (in square brackets) and the number of articles published. Non-journal sources are given an Impact Factor of zero.

- **USA [4.10] 14750** (*Applied Physics Letters* [4.13] 862, *Physical Review B* [3.19] 729, *Journal of Applied Physics* [2.50] 517, *Journal of Physical Chemistry B* [4.03] 506, *Journal of the American Chemical Society* [7.42] 449)
- **Peoples Republic of China [1.98] 11746** (*Rare Metal Materials and Engineering* [0.40] 348, *Materials Letters* [1.30] 313, *Chinese Journal of Inorganic Chemistry* [0.70] 271, *Journal of Physical Chemistry B* [4.03] 270, *Applied Physics Letters* [4.13] 261)
- **Japan [2.33] 7971** (*Japanese Journal of Applied Physics Part 1** [1.10] 522, *Applied Physics Letters* [4.13] 338, *Physical Review B* [3.19] 237, *Journal of Applied Physics* [2.50] 193, *Japanese Journal of Applied Physics Part 2** [1.10] 170)
- **Germany [3.99] 5665** (*Physical Review B* [3.19] 377, *Applied Physics Letters* [4.13] 219, *Journal of Applied Physics* [2.50] 158, *Physical Review Letters* [7.49] 142, *Journal of Physical Chemistry B* [4.03] 117)
- **South Korea [1.50] 4098** (*Journal of the Korean Physical Society* [0.83] 280, *Applied Physics Letters* [4.13] 170, *On the Convergence of Bio-Information-, Environmental-, Energy-, Space- and Nano-Technologies, Pts 1 and 2* [0.00] 157, *Thin Solid Films* [1.57] 101, *Japanese Journal of Applied Physics Part 1** [1.10] 85)
- **France [3.72] 3994** (*Physical Review B* [3.19] 227, *Applied Physics Letters* [4.13] 149, *Journal of Applied Physics* [2.50] 113, *Physical Review Letters* [7.49] 97, *Langmuir* [3.71] 78, *Thin Solid Films* [1.57] 78)

*Note: one SCI Impact Factor for *Japanese Journal of Applied Physics* given, no separate Impact Factors for each part.

There is a clear distinction between the three Western nations and the three Asian nations. The Western nations have average Impact Factors within 5% of 3.9, while the Asian nations are within 10% of 2.13 (excluding the non-SCI proceedings in South Korea's top five), almost a factor of two difference. Much of the difference comes from the Asian nations publishing a not-insignificant fraction of their output in domestic journals (most of which have low Impact Factors), while the Western nations publish almost exclusively in international journals. Whether this stems from problems with the English language or easier publication acceptance cannot be discerned from the present data.

Additionally, some of the Asian countries are publishing in journals whose initial access date in the SCI/SSCI is relatively recent. For example, the median initial SCI/SSCI access date for the five journals (above) in which the USA published nanoscience/nanotechnology articles most frequently is 1962, whereas the median initial access date for China is 1997. This initial access date phenomenon was discovered recently in a comparison of India'a and China's published research outputs

(KOSTOFF et al, 2006d), where it was shown that for the twenty journals in which China (in aggregate) published most frequently, their median initial SCI/SSCI access date was 1995, whereas for the twenty journals in which India (in aggregate) published most frequently, their median initial SCI/SSCI access date was 1970.

Why is this difference in median access dates important in the present nanotechnology study, or in the India-China comparison study? Both these studies place some emphasis on growth in research article production. Increased production is ordinarily assumed to be due to increased research sponsorship and/or increased research productivity. However, a neglected source of 'increased production' is access to the articles of a journal that had not been accessed previously. If China, for example, is publishing a non-negligible fraction of its research output in newly-accessed relatively low Impact Factor journals (as appeared to be the case examined in the India-China comparison), then some of its apparent growth will not be in the traditional sense of increased sponsorship or productivity, but rather due to the SCI/SSCI's decision to access existing journals' articles. From another perspective, the reality may be that China's research article production may have been somewhat more competitive for decades, but was artificially suppressed by many of its journals' non-inclusion in the SCI/SSCI until only recently.

For example, the first journal above listed for China, Rare Metal Materials and Engineering, has been published since 1970, but was first accessed by the SCI/SSCI in 1997. In doing an SCI-based comparison of pre- and post- 1997 research article production for China, any articles published in Rare Metal Materials and Engineering would be registered as research production growth for China, even though it is in actuality a book-keeping artifice relative to growth.

To identify country-country collaborations for the major research article producers, a country-country co-occurrence matrix was generated. The five most prolific countries, and their major collaborators, are presented (collaborator, # co-authored papers):

Results from co-occurrence matrix for top five most prolific countries (number of records in common listed in the parentheses):

- **USA** (Germany 604, Peoples R China 498, Japan 441, South Korea 423, France 300);
- **Peoples R China** (USA 498, Japan 304, Germany 178, Singapore 154, South Korea 110);
- **Japan** (USA 441, Peoples R China 304, South Korea 218, Germany 144, France 124);
- **Germany** (USA 604, France 352, Russia 290, England 194, Peoples R China 178);
- **South Korea** (USA 423, Japan 218, Peoples R China 110, India 56, Russia 38, England 38).

The USA was the chief collaborator with the other four countries, and China and Japan vied for the position of second-most prolific collaborator, except for the case of Germany, where France was second most prolific collaborator. The above results measure the absolute value of the amount of collaboration between two countries; hence the top collaborators with the big players are very prolific countries themselves. Singapore and India are the only collaborators listed that are not in the top ten, and they worked together extensively with China and South Korea, respectively.

Results from percentage co-occurrence matrix for top five most prolific countries (percent of records in common listed in the parentheses):

- **USA** (Israel 18.9%, Canada 15.5%, Denmark 15.4%, Mexico 15.3%, Turkey 12.7%);
- **Peoples R China** (Singapore 14.7%, Australia 8.4%, Canada 4.2%, Japan 3.8%, Sweden 3.8%);
- **Japan** (Czech Republic 7.6%, South Korea 5.3%, Australia 4.5%, India 4.2%, England 3.7%);
- **Germany** (Austria 23.9%, Switzerland 17.2%, Czech Republic 16.6%, Ukraine 13.7%, Russia 13.3%);
- **South Korea** (USA 2.9%, Japan 2.7%, India 2.7%, Ukraine 2.2%, Russia 1.7%).

The above list shows countries that co-published a high proportion of articles with one of the five most prolific countries. For instance, 18.9% of Israel's nanoscience/ /nanotechnology articles were co-authored with the USA. This analysis takes the emphasis away from more prolific collaborators that have a large number of co-authored articles, even though this represents only a small fraction of that country's total nanotechnology output.

The United States' neighbors and strategic allies published many of their research articles together with the US, and similarly Germany's top collaborators are in geographic proximity, in Central/Eastern Europe. The percentages associated with these two countries are high, while South Korea has low percentages associated with it. Japan and China have moderate percentages associated with them, with the exception of Singapore's collaboration with China. Collaboration between these countries is given more value in this table, and there are some unexpected occurrences, such as the Czech Republic's considerable cooperation with Japan.

The USA's and China's global positions in nanotechnology are made clearer by the country auto-correlation map (Figure 5a). Although both publish extensively with other nations, no linkages show up on the map. The two powerhouses appear at two poles of Figure 5a. This means that the US and China co-authorships are very distributed, and not heavily tied to any other countries relative to US and China total publications.

The only significant, although weak, connections are among European countries, and this complex web of nations roughly follows geographic lines. Norway, Denmark, Sweden, and Finland make up a Nordic group; the Netherlands, Belgium, Austria, Switzerland, and Germany constitute Central Europe; and the Eastern European group is made up of Romania, the Czech Republic, Slovakia, Poland, Ukraine, Belarus, Russia, Bulgaria, Hungary, and Lithuania. Brazil, Argentina, Portugal, Spain, Mexico, France, and Italy compose a group of Romance language nations. The individual groups can be distinguished based on geographic and/or linguistic similarities, but the connections stretch across, and beyond, the continent of Europe.

Outside of the network containing the other European nations, the United Kingdom's countries (Northern Ireland, England, Scotland, and Wales) and Ireland are linked. Also, Australia and New Zealand are connected, and there is an East/Southeast Asian group consisting of extremely weak links among South Korea, Taiwan, Thailand, and Singapore. The United Kingdom is not linked to the interconnected continental members of the European Union.

A more quantitative perspective on country connections can be obtained from factor analysis. Table 7 shows a seven factor matrix for the top forty countries.

Seven groupings are shown, one for each factor.

Factor 1 – England strongly linked to Scotland, weakly linked to Ireland and Australia, and very weakly linked to New Zealand;

Factor 2 – China and Japan strongly linked, but in combination not linked to South Korea (East Asia);

Factor 3 – Japan strongly linked to South Korea (but in combination not linked to China), and weakly linked to India;

Factor 4 – Sweden strongly linked to Norway, Denmark, and the Netherlands; and weakly linked to Finland;

Factor 5 – France strongly linked to Belgium, Italy, and Spain; and weakly linked to Romania and the Netherlands;

Factor 6 – Germany strongly linked to Russia, Ukraine, Austria, and Poland; and weakly linked to Bulgaria;

Factor 7 – Argentina strongly linked to Brazil, Mexico, Portugal, and Spain.

Adding more institutions should emphasize further the cooperation present in Europe. Also, the US is far on the opposite tail of the Japan/China theme, which means that there are proportionally few American authors on papers with Japanese and Chinese authors.

Figure 5b contains a country–phrase cross-correlation map. While the US and China represent two poles as in Figure 5a, the US pole is strongly connected thematically to a densely connected network, whereas China is relatively isolated except for India. The densely connected network consists of the English-speaking North American representatives, Western/Central European nations, and most of the East Asian allies. The Eastern European and Latin American representatives tend to be outside the dense network.

Table 7. Seven factor matrix (forty most prolific countries)

Factor	1	2	3	4	5	6	7
England	***–0.632***	0.254	–0.003	–0.04	–0.109	–0.024	–0.006
Scotland	***–0.519***	0.2	–0.028	0.059	–0.018	0.022	0.039
Ireland	*–0.295*	0.083	0.01	–0.096	0.013	0.019	–0.005
Australia	*–0.226*	0.064	–0.052	–0.058	0.058	–0.057	–0.037
New Zealand	–0.183	0.066	–0.006	0.013	0.022	–0.014	–0.012
Iran	–0.129	0.061	0.009	0.039	0.002	–0.031	–0.02
Peoples R China	–0.053	***–0.547***	***–0.666***	0.161	*0.228*	*–0.225*	–0.057
Japan	–0.04	***–0.371***	***0.703***	0.026	0.124	–0.112	–0.107
South Korea	0.038	0.014	***0.304***	0.071	0.18	–0.102	–0.036
India	–0.022	–0.046	*0.205*	0.036	0.005	–0.07	0.002
Sweden	–0.012	–0.066	–0.025	***–0.541***	0.053	0.096	0.01
Norway	–0.025	0.012	–0.027	***–0.469***	0.005	–0.096	0.008
Denmark	–0.013	0.006	–0.022	***–0.463***	0.013	–0.01	0.03
Netherlands	0.046	–0.025	–0.039	***–0.376***	*–0.259*	–0.094	–0.187
Finland	–0.069	–0.049	0.016	*–0.232*	0.039	0.117	0.025
France	0.022	–0.024	0.019	0.095	***–0.532***	0.082	0.019
Belgium	0.136	–0.04	–0.054	–0.184	***–0.409***	–0.108	–0.198
Italy	–0.03	0.049	0.004	0.055	***–0.37***	0.02	–0.093
Spain	–0.077	–0.017	–0.003	–0.033	***–0.344***	–0.017	***0.384***
Romania	0.019	–0.013	0.043	0.136	*–0.296*	–0.026	–0.196
Switzerland	–0.016	0.105	–0.041	–0.022	–0.186	0.118	*–0.209*
Germany	0.013	0.047	–0.089	–0.011	–0.085	***0.565***	–0.094
Russia	0.022	–0.007	0.03	–0.133	0.088	***0.39***	0.033
Ukraine	0.031	–0.017	–0.005	–0.065	0.167	***0.363***	*0.213*
Austria	–0.003	0.019	–0.039	0.015	–0.042	***0.351***	–0.116
Poland	0.084	–0.032	0.009	0.004	0.01	***0.351***	0.107
Bulgaria	0	–0.016	–0.015	0.064	–0.044	*0.222*	–0.023
Greece	–0.034	0.049	–0.014	0.163	–0.039	0.178	–0.048
Argentina	0.066	–0.01	–0.007	0.039	–0.16	–0.063	***0.506***
Brazil	0.078	0	0.019	0.037	–0.17	–0.09	***0.425***
Mexico	0.076	0.005	0.011	–0.024	–0.035	–0.007	***0.323***
Portugal	–0.08	–0.049	–0.004	–0.067	–0.073	0.095	***0.306***
Taiwan	–0.04	–0.025	0.072	0.053	0.12	–0.028	0.051
USA	***0.418***	***0.745***	–0.065	–0.012	*0.212*	–0.185	–0.006
Israel	0.103	0.104	–0.048	0.023	–0.036	0.033	–0.008
Canada	0.002	0.149	–0.051	0.076	–0.028	–0.019	–0.028
Singapore	–0.029	–0.016	–0.187	0.027	0.067	–0.084	–0.053
Turkey	–0.065	0.082	0.021	0.079	0.025	0.05	–0.057
Hungary	0.052	–0.007	–0.03	–0.046	–0.102	0.131	–0.096
Czech Republic	0.089	–0.083	0.055	0.041	–0.149	0.174	–0.129

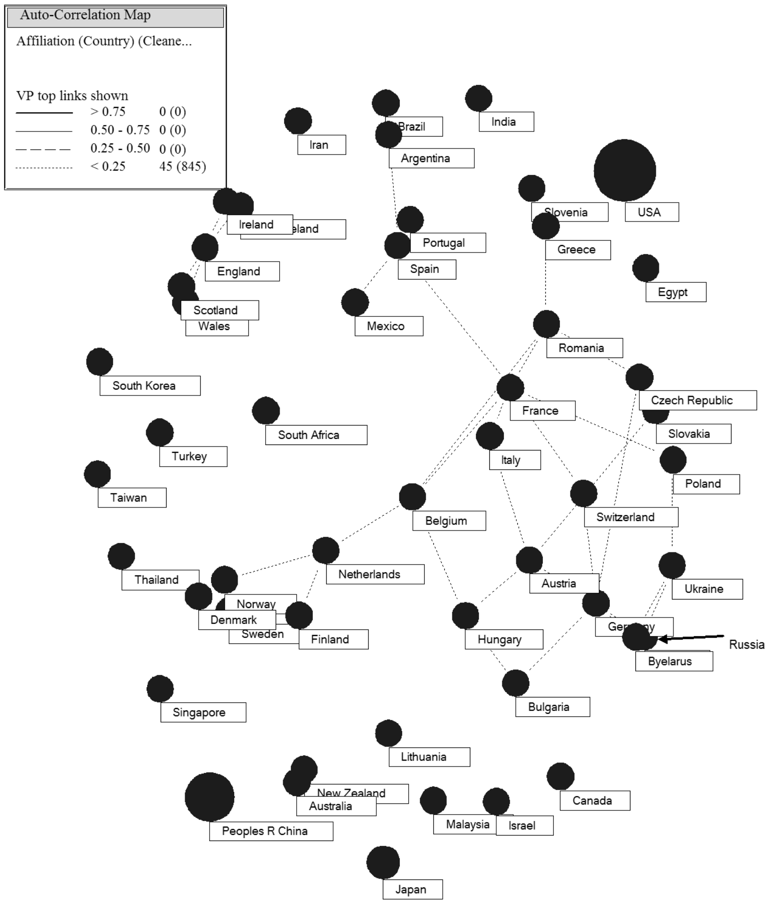

Figure 5a. Country auto-correlation map (fifty most prolific countries)

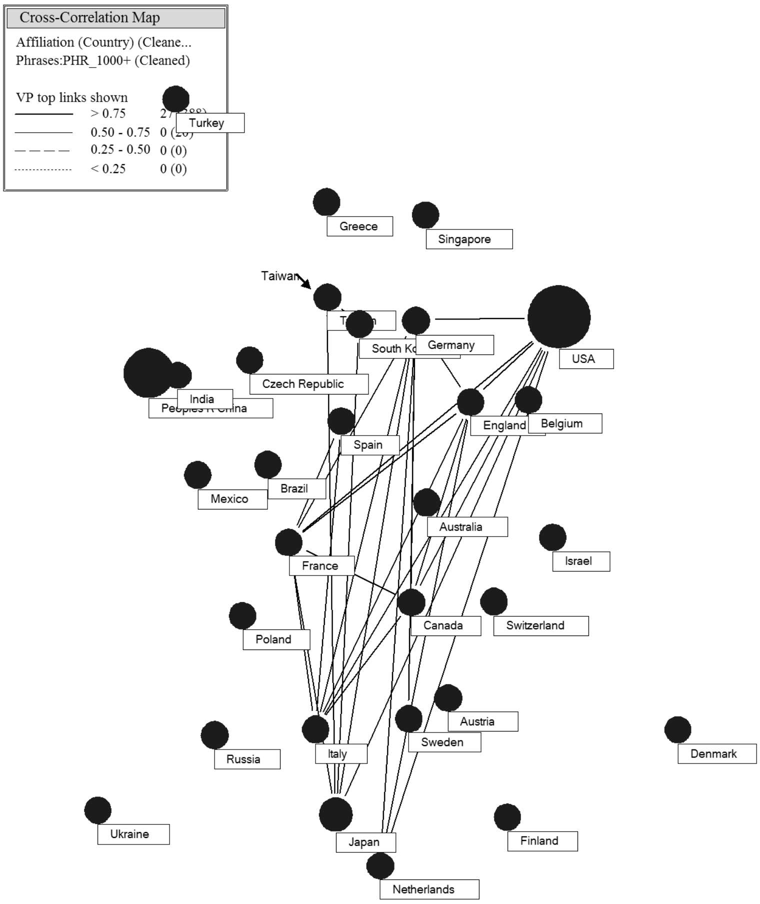

Figure 5b. Country–phrase cross-correlation map (top thirty countries)

Most cited journals

Table 8 contains the thirty most cited journals. Of the top thirty journals in which nanotechnology authors publish and those that they cite, twenty overlap. This is consistent with past text mining studies. The very top journals on the most cited list are weighted toward physics, while the bottom journals are weighted toward chemistry. There tend to be recognizably more materials journals in the list of prolific journals than in the cited journals list. The median Impact Factor of the thirty journals in which nanotechnology authors publish most is 2.50, while the median Impact Factor of those they cite most is 4.03. However, the median Impact Factor of the journals on the most cited list but not on the most published list is 7.62.

Table 8. Most cited journals

Journal	Times cited	Impact factor	Theme
PHYS REV B	71207	3.19	PHYS
APPL PHYS LETT	68026	4.13	PHYS
J AM CHEM SOC	53417	7.42	CHEM
PHYS REV LETT	51648	7.49	PHYS
J PHYS CHEM*	45268	2.90 (A), 4.03 (B)*	CHEM
SCIENCE	41776	30.93	SCIENCE
J APPL PHYS	35439	2.50	PHYS
NATURE	34914	29.27	SCIENCE
LANGMUIR	33387	3.71	CHEM
MACROMOLECULES	24282	4.02	CHEM
CHEM MATER	21792	4.82	CHEM
J CHEM PHYS	20431	3.14	PHYS
ADV MATER	19534	9.11	MATLS
ANGEW CHEM INT EDIT	17777	9.60	CHEM
THIN SOLID FILMS	14574	1.57	MATLS
CHEM PHYS LETT	13561	2.44	PHYS
J ELECTROCHEM SOC	12929	2.19	CHEM
SURF SCI	12190	1.78	MATLS
ANAL CHEM	12040	5.64	CHEM
POLYMER	11452	2.85	MATLS
P NATL ACAD SCI USA	10723	10.23	SCIENCE
J CRYST GROWTH	9708	1.68	MATLS
INORG CHEM	9628	3.85	CHEM
CHEM REV	9366	20.87	CHEM
J CATAL	9275	4.78	CHEM
NANO LETT	8915	9.85	NANO
J MATER CHEM	8533	3.69	MATLS
CHEM COMMUN	8501	4.43	CHEM
J COLLOID INTERF SCI	8244	2.02	CHEM
J AM CERAM SOC	8025	1.59	MATLS

[*] Note: The *Journal of Physical Chemistry* counts all papers published in the *Journal of Physical Chemistry* (which existed from 1896-1996), the *Journal of Physical Chemistry A*, and the *Journal of Physical Chemistry B* (the latter two which were created in 1997). The Impact Factors for both the *Journal of Physical Chemistry A* and the *Journal of Physical Chemistry B* are given.

There appear to be four major journal groups. The first group consists of the two most cited journals (*Physical Review B*, *Applied Physics Letters*), both physics journals. The second group (*Journal of the American Chemical Society*, *Physics Review Letters*, *Journal of Physical Chemistry*, *Science*) has more of a physical chemistry emphasis, the third group (the next eight journals on the list) is chemistry-dominated, and the fourth group (the next sixteen journals on the list) is essentially split between chemistry and materials. The general science journals in Table 8 have the highest Impact Factors, followed by chemistry, physics, and materials journals, in that order.

Authors of most cited nanoscience/nanotechnology papers

To identify all the authors most associated with the highly cited nanoscience/nanotechnology-focused papers, the 401 nanoscience/nanotechnology-related documents cited most highly (as listed in the SCI) from 1991 to 2003 were retrieved, and the author frequency was extracted. The papers were chosen by selecting all the articles between 1991 (the first year that Abstracts were included in SCI records) and 2001 that had 400 citations or more and the 30 most cited articles from 2002 and 2003. This method of author extraction includes all the paper authors, not limited to first author. Table 9 shows the results. The well-known authors in nanoscience/nanotechnology are clearly evident from this result.

Table 9. Authors of (401) most cited papers since 1991

Author	Number of papers	Institution	Country
Smalley, RE	15	RICE UNIV	USA
Lieber, CM	13	HARVARD UNIV	USA
Mirkin, CA	11	NORTHWESTERN UNIV	USA
Alivisatos, AP	10	UNIV CALIF BERKELEY	USA
Dai, HJ	10	STANFORD UNIV	USA
Whitesides, GM	10	HARVARD UNIV	USA
Rinzler, AG	8	UNIV FLORIDA	USA
Colbert, DT	7	NGEN	USA
Dekker, C	7	DELFT UNIV TECHNOL	Netherlands
Thess, A	6	M-PHASYS GMBH	Germany
Ebbesen, TW	5	UNIV STRASBOURG 1	France
Gratzel, M	5	ECOLE POLYTECH FED LAUSANNE	Switzerland
Nikolaev, P	5	ERC INC/JOHNSON SPACE CENTER	USA
Yang, PD	5	UNIV CALIF BERKELEY	USA

Note that the top eight highly cited authors are from the US, Hongjie Dai worked as postdoctoral fellow in Lieber's group at Harvard University and in Smalley's group at Rice University and that Rinzler, Colbert, Thess, and Nikolaev were part of the Smalley group before holding their current positions. Yang is a former member of Lieber's research group as well, so not only is there some overlap in the authors of the most cited papers, but their current institution does not necessarily correspond to where they published one of the seminal works of 1991 to 2003. Ten of the fourteen insitutions of the seminal nanotechnology papers' authors are in the USA, and the remaining four are in Central Europe.

Table 10 lists the journals that contain the most highly cited nanoscience/nanotechnology papers. The eighteen journals have a relatively high median Impact Factor of 9.36. In fact, *Science*, *Reviews of Modern Physics*, and *Nature* are journals with the sixth, eighth, and eleventh highest Impact Factors, respectively, in the SCI. Furthermore, these three journals have the highest Impact Factors for multi-disciplinary or physical science journals, having only medical or biological sciences journals ahead of them. The pivotal nanotechnology articles appeared primarily in journals of general science, physics, chemistry, and materials science. The journals *Science* and *Nature* clearly stand out as the publication venues of choice for the leading nanotechnology papers.

Table 10. Top 18 journals of (401) most cited papers

Journal	Number of papers	Impact factor	Theme
Science	113	30.93	SCIENCE
Nature	71	29.27	SCIENCE
Physical Review Letters	23	7.50	PHYS
Applied Physics Letters	15	4.13	PHYS
Chemical Reviews	13	20.87	CHEM
Advanced Materials	12	9.11	MATLS
Journal of the American Chemical Society	12	7.42	CHEM
Accounts of Chemical Research	9	13.14	CHEM
*Journal of Physical Chemistry**	8	4.03	CHEM
Angewandte Chemie-International Edition in English	7	9.60	CHEM
Journal of Applied Physics	7	2.50	PHYS
Physical Review B	6	3.19	PHYS
Reviews of Modern Physics	6	30.25	PHYS
Cell	5	29.43	BIO
Proceedings of the National Academy of Sciences of the USA	5	10.23	SCIENCE
Chemical Physics Letters	4	2.44	CHEM
Langmuir	4	3.71	CHEM
Physics Reports – Review Section of Physics Letters	4	10.46	PHYSICS

[*] Note: The *Journal of Physical Chemistry* refers to both papers published in the *Journal of Physical Chemistry* (which existed from 1896-1996) and the *Journal of Physical Chemistry B* (which along with the *Journal of Physical Chemistry A* existed from 1997 onwards). The Impact Factor cited refers to the Impact Factor for the *Journal of Physical Chemistry B*.

As shown in Table 11, the US outpaced the rest of the world in terms of authorship of the most cited papers between 1991 and 2003. The US had more than four times as many highly cited papers as its closest competitor, Germany, and more highly cited papers than the next eight countries combined. This table re-emphasizes the mismatch between China's and South Korea's high publication productivity and yet low impact (citations). Authors from China and South Korea publish many papers, but the papers are not cited highly. The reason for this phenomenon remains unclear, and is worth further investigation.

As shown in Table 12, twenty-two of the institutions are universities, and all but four of the top twenty-five research institutions of the authors of the most cited nanotechnology articles from 1991 to 2003 are in the US. This is contrasted with Table 4, where only four of the thirty most prolific institutions are in the US. This is further confirmation of the high US impact on nanotechnology.

Table 11. Top 18 countries of (401) most cited papers

Country	Number of records
USA	126
Germany	31
France	19
Japan	19
Netherlands	17
England	15
Switzerland	10
Italy	7
Australia	6
Canada	5
Israel	5
Peoples R China	5
Russia	5
Sweden	4
Belgium	3
South Korea	2
Spain	2
Taiwan	2

Table 12. Top 25 institutions of (401) most cited papers

Institution	Country	Number of papers
HARVARD UNIV	USA	27
UNIV CALIF BERKELEY	USA	23
RICE UNIV	USA	17
UNIV CALIF SANTA BARBARA	USA	16
IBM CORP	USA	12
NORTHWESTERN UNIV	USA	12
DELFT UNIV TECHNOL	Netherlands	11
MIT	USA	10
UNIV ILLINOIS	USA	9
STANFORD UNIV	USA	9
MICHIGAN STATE UNIV	USA	7
GEORGIA INST TECHNOL	USA	6
PURDUE UNIV	USA	6
CALTECH	USA	5
CORNELL UNIV	USA	5
PENN STATE UNIV	USA	5
CNRS	France	4
UNIV PENN	USA	4
UNIV CAMBRIDGE	UK	4
UNIV WISCONSIN	USA	4
UNIV TOKYO	Japan	4
UNIV TEXAS	USA	4
UNIV KENTUCKY	USA	4
SWISS FED INST TECHNOL	Switzerland	4
USN	USA	4

Summary and conclusions

Global nanotechnology research article production has exhibited exponential growth for more than a decade. This growth is a worldwide phenomenon, but the most rapid growth over that time period has come from East Asian nations, notably China and South Korea. However, some of this apparent rapid growth (in China for example) is partially due to a non-negligible fraction of domestic low Impact Factor journals recently being accessed by the SCI/SSCI, rather than by increased sponsorship or productivity. While the US remains the leader in aggregate nanotechnology research article production, in some selected nanotechnology sub-areas, China has achieved parity or taken the lead.

Institutional and country links offer some useful insights. The main institution co-publishing groups are East Asian: one each from China, Japan, and South Korea. Publication connectivity among institutions is much weaker than common interest or citation connectivity. Correlation of institutions by the journals they cite reveals four nationality-based (or locality-based) clusters: Chinese, Japanese, American, and European. Institutions from the same nationality group cite the same focused journals (primarily, but not exclusively, domestic). Correlation of institutions by documents they cite reveals only the Chinese institutions constitute a strongly-connected network.

The dominant country co-publishing network is a complex web of mainly European nations roughly following geographic lines: Nordic, Central Europe, Eastern Europe, and a Western Europe/Latin American group of Romance language nations. There is also a UK component country network, but it is not linked to the interconnected continental members of the European Union. Correlation of countries by common thematic interest shows two major poles: US and China. The US pole is strongly connected thematically to a densely connected network of English-speaking North American representatives, Western/Central European nations, and most of the East Asian allies. China is relatively isolated except for India, and the Eastern European and Latin American representatives are outside the main network as well.

There is a clear distinction between the publication practices of the three most prolific Western nations and the three most prolific East Asian nations. The Western nations publish in journals with almost twice the weighted average Impact Factors of the East Asian nations. Much of the difference stems from the East Asian nations publishing a non-negligible amount in domestic low Impact Factor journals, while the Western nations publish in higher Impact Factor international journals.

Of the thirty institutions publishing the most nanotechnology papers, four are from the US, whereas of the twenty-five institutions producing the most cited papers, twenty-one are in the US. The two journals that contain the most cited nanotechnology papers since 1991 are *Science* and *Nature*, and the two countries that lead in production of the most cited papers are the US and Germany, with the US having four times the number of most cited papers as Germany. The US and Germany account for forty percent of the most cited papers, while the high paper volume production East Asian countries of China and South Korea account for two percent of the most cited papers. Despite the increased paper productivity from East Asian countries, the US continues to make the most impact on nanotechnology.

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