Nanotechnology-interdisciplinarity, patterns of collaboration and differences in application

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NANOTECHNOLOGY – INTERDISCIPLINARITY, PATTERNS OF COLLABORATION AND DIFFERENCES IN APPLICATION

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Nanotechnology is a novel technological field said to be one of the key technologies in the 21st century revolutionizing information technology, materials and medicine. Bibliometric quantification is a way to show the emergence of a new technology. *Braun* et al.[1] could establish an exponential growth pattern of publications in nano-science and technology starting in the early 1990s. Using their study as basis we intend to further characterize nanotechnology using bibliometric as well as patent data. We can show that the share of boundary-spanning publications is exceptionally high in the field of nanotechnology. Our co-authorship analysis indicates that countries follow different patterns of collaboration. Some countries tend to have bilateral relations while others collaborate with a much larger array of nations. Patent data in combination with bibliometric reveals differences in the application of science. In our conclusion we raise a number of questions requiring an analysis using also other types of data. Still, a closer investigation and disaggregation of bibliometric data may come up with additional findings.

Introduction

Nanotechnology is an emerging technological field. As a recent study shows, there is little consensus on what exactly is nanotechnology.[2] However, *Franks*' definition[3] of nanotechnology as *'the technology where dimensions or tolerances in the range 0.1 to 100 nm (from the size of an atom to the wavelength of light) play a critical role'* seems to have commanded wide acceptance.[4] In practice, the label 'nanotechnology' also includes methods used to build structures up to a micron.[5] A number of technology foresight studies[4,6–11] identify nanotechnology as a key technology in the 21st century revolutionizing information technology, materials and medicine.

Bibliometric quantification is a way to show the emergence of a new technology. In their study, *Braun* et al., could show that a new scientific and technological field has

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been born. They could establish an exponential growth pattern of publications in nano-science and technology starting in the early 1990s.

While the Braun study emphasized the emergence of the field as such, we see our paper as a contribution to characterize nanotechnology. Mostly following the approach chosen by *Braun* et al., we can show the interdisciplinary nature of nanotechnology. We also look at differences among countries. By including patent data in our study we can illustrate the impact nations have on the emergence of a technology.

Method

As far as possible we used the approach chosen by *Braun* et al. when counting nano-papers in the *Science Citation Index.* As *Braun* et al., we retrieved articles that contained the prefix 'nano' in their title. We excluded a smaller number of terms as irrelevant to the topic, such as nanosecond, nanoampere, nanogram.[12] Already the exclusion of a few irrelevant terms brought us close enough to Braun's results. Table 1 shows how close our results have come to those of *Braun* et al. The small differences between our and Braun's study demonstrate the reliability and replicability of their study.

Table 1
Comparison of our sample of nano-papers with *Braun* et al.

Publication year	N of articles in our study	N of articles in *Braun* et al
1991	274	254
1992	450	425
1993	686	545
1994	1047	1049
1995	1366	1406
1996	1607	n.a.

Interdisciplinarity

Distribution of papers by field

Using our database, we had a look at the distribution of nano-papers according to the journal based classification developed by *Katz* and *Hicks.*[13] As Table 2 indicates, most nano-papers are published in the major field of natural sciences. However, multidisciplinary publications and papers in the engineering and materials sciences play a prominent role. Especially the strong position of multidisciplinary papers is striking.

Table 2
Distribution of papers by major field by SPRU-classification

Major field	1991	1992	1993	1994	1995	1996	Total	Growth[a]	Standard Error
Natural Sciences	119	205	386	612	765	946	3033	3.2	3.7
Multidisciplinary Sciences	51	103	141	189	289	367	1140	0.4	2.2
Engineering and Materials	74	92	127	184	235	209	921	-2.3	1.9
Life Sciences	30	47	30	59	70	56	292	-1.5	1.8
Unknown[b]	0	0	0	1	5	24	30	0.2	0.4
Total	274	447	684	1045	1364	1602	5416		

[a] The growth rate is calculated as a linear slope coefficient based on the annual shares of the respective major fields.
[b] The SPRU-classification scheme is based on ISI 1994 journal set. ISI add journals and drop journals. Ten of the 30 unknown papers are in journals without ISI-classification anymore; the remainder of 20 unclassified papers has been published in newly added journals.

The subfield-distribution underlines this finding (Table 3) which shows the interdisciplinary character of research in nanotechnology. Counting all interdisciplinary subfields, one obtains, as seen, a total of 1140 papers. If one adds the 154 interfield nanopapers, one comes to a number of 1299 papers that are of a cross-boundary nature. Altogether, cross-boundary subgroups would take rank 2 after physical sciences. In *Hicks*' and *Katz*' study,[13] 81 percent of all UK papers were published in single-field journals while the corresponding figure for the nano-papers were 72 percent.

The subfield classification underpins also the importance of materials. This is plausible given the nature of materials and engineering as interdisciplinary sciences. Counting all materials-related papers one comes to a total of 1807. This is almost as much as can be found for physics.

Growth

Looking at the percentage distribution of nano-papers one can establish some trends. We calculated a linear slope coefficient based on the annual shares of major fields as well as subfields (*Growth* columns in Tables 2 and 3). While natural and multidisciplinary sciences have gotten stronger, the major fields of engineering and materials and life sciences seem to have lost importance. Papers in natural science have a slope coefficient of 3.2. The only other growing field is multidisciplinary sciences with 0.4. Engineering and materials as well as life sciences lost ground dramatically. Their shares dropped by more than a half and three forths, respectively, leading to coefficients of -2.3 and -1.5.

Table 3
The subfield distribution of nano-papers by SPRU-classification

Subfield	1991	1992	1993	1994	1995	1996	Total	Growth[a]	Standard Error
Physical sciences	74	132	266	387	420	548	1827	1.1	4.6
Chemical sciences	40	70	107	215	334	375	1141	2.2	1.8
Interdisciplinary natural-engineering & materials science	26	67	92	144	211	286	826	1.2	1.6
Materials science	57	75	99	133	185	153	702	-1.9	1.4
Interdisciplinary life-natural-engineering & materials science	15	22	38	30	58	59	222	-0.4	0.9
Medical sciences	20	30	21	39	42	34	186	-1.0	1.0
Engineering sciences	14	12	18	33	39	39	155	-0.4	0.8
Interdisciplinary life-natural sciences	10	14	11	15	20	22	92	-0.5	0.5
Biological sciences	7	7	7	12	15	10	58	-0.3	0.4
Interfield engineering and material sciences	3	4	8	18	10	14	57	0.0	0.4
Interfield natural sciences	2	3	10	8	11	21	55	0.1	0.3
Interfield life sciences	2	9	2	8	11	10	42	-0.1	0.6
Earth sciences	2	0	3	2	0	2	9	-0.1	0.3
Information and communications	0	1	2	0	1	3	7	0.0	0.1
Agricultural sciences	1	1	0	0	2	2	6	0.0	0.1
Mathematical science	1	0	0	0	0	0	1	-0.1	0.1
Unknown[b]	0	0	0	1	5	24	30	0.2	0.4
Total	274	450	686	1047	1366	1607	5416		

a The growth rate is calculated as a linear slope coefficient based on the annual shares of the respective major fields.

b The SPRU-classification scheme is based on ISI 1994 journal set. ISI add journals and drop journals. Ten of the 30 unknown papers are in journals without ISI-classification anymore; the remainder of 20 unclassified papers has been published in newly added journals.

A look at the subfield results gives a more detailed view. There we see that the growth of nano-papers with a natural science classification is not uniform. Thus the slope of chemical nano-publications is twice as steep as the one of physical nano-papers.

The growth in share of nano-papers in the major field of multidisciplinary publications is due to the subfield of interdisciplinary natural-engineering and materials science. While the shares of other multidisciplinary sciences are decreasing, this subfield could increase its share by more than a third. Its slope coefficient equals 1.2. An interesting observation in this connection is the decrease in share of publications in materials science (-1.9). Since this is more than what happened to the other multidisciplinary fields one may ask if there is then a general trend in nanoscale materials towards interdisciplinarity.

Patterns of collaboration

The key players

With our database we could identify the leading countries in nanopapers. Not surprisingly, the US, Japan and Germany are heading the list. An interesting finding, however, is the relatively strong position of China. Table 4 shows the distribution of papers by country.

Table 4
The distribution of papers by country (with duplicate country addresses removed)

Country	1988	1989	1990	1991	1992	1993	1994	1995	1996	Total
USA	1	1	5	117	183	282	372	530	571	2062
Japan	0	0	3	26	49	83	122	152	214	649
Germany	0	0	3	39	52	61	106	127	159	547
France	1	0	4	21	45	60	98	124	152	505
PR China	0	0	0	8	21	44	71	91	110	345
UK	0	1	1	8	22	21	68	52	76	249
Russia[a]	0	0	0	6	18	32	25	69	69	219
Spain	0	0	0	9	9	19	39	46	40	162
Canada	0	0	0	15	12	17	23	49	36	152
Italy	0	0	0	4	15	20	28	38	43	148
All Countries	2	2	20	300	509	759	1195	1583	1776	6146

[a] Russia includes counts for what used to be the Soviet Union.

A look at the institutions publishing seems to underline our results for the countries (Table 5). Japanese and American institutions are heading the list with the Chinese Academy of Sciences as no.1.

Table 5
Papers by institutions

# Papers	Institutions	Home countries
166	Acad Sinica	PR China
135	MIT	USA
127	Univ Calif Berkeley	USA
125	Tohoku Univ	Japan
114	Univ Illinois	USA
107	Russian Acad Sci	Russia
106	USN	USA
81	Univ Paris 11	France
81	IBM Corp	USA
75	Jilin Univ	PR China

Co-authorship analysis

We conducted a co-authorship analysis. Figure 1 illustrates our results in a country co-authorship matrix. An interesting finding is that, looking at the leading countries, one can distinguish different patterns of collaborations. On the one hand, there are countries whose researchers collaborate with colleagues from a variety of countries. On the other hand, researchers in certain other countries prefer to co-author papers with colleagues in only a few other countries.

Thus the US with 311 out of 1538 co-authorships are cooperating with every country included in this matrix. Germany and France come quite close to this range of collaborations. However, Japan and China, countries that are big in publishing, do not collaborate internationally to the same extent. They seem to collaborate selectively with the other leading countries only. Japan seems to have serious collaborations only with the US, Germany, France, the UK and China. China itself has close collaborations with Germany, the US and Japan. This restricted set of rather intensive collaborations, as we can observe it for China and to a certain extent for Russia too, raises the question whether it is science quality or science policy that is creating the links. Are there any major breakthroughs coming from these countries, as the high number of nanopapers from China and Russia might suggest, or is it just a matter of science policies establishing these collaborations?

COUNTRY CO-AUTHORSHIP MATRIX	AUSTRALIA	BELGIUM	BRAZIL	CANADA	DENMARK	FRANCE	GERMANY	INDIA	ISRAEL	ITALY	JAPAN	MEXICO	NETHERLANDS	PR CHINA	POLAND	RUSSIA	SOUTH KOREA	SPAIN	SWEDEN	SWITZERLAND	TAIWAN	UK	USA
AUSTRALIA				3		1	5				1						1	1		2		1	5
BELGIUM					1	9	1		2				1	1		3		1	1			3	13
BRAZIL				1		1	4		1	5								2		6			4
CANADA	3		1			5	5	2			2		1							2		1	34
DENMARK		1					4		1	1	1		2			1			3				4
FRANCE	1	9	1	5			22	2	9	23	5	1	6	4	1	10		26	2	7		11	31
GERMANY	5	1	4	5	4	22		1	4	9	10		10	20	13	15	2	10	1	15		14	46
INDIA				2		2	1			2				1				2				1	6
ISRAEL		2	1		1	9	4								1				1			4	12
ITALY			5		1	23	9	2			1		2	1		2		4	1	6		2	7
JAPAN	1			2	1	5	10			1			2	5	2	3	3	1			1	8	43
MEXICO						1												4				4	9
NETHERLANDS		1		1	2	6	10			2	2			1	1	2		2	1	2		4	5
PR CHINA		1				4	20	1		1	5		1		3	3	1						13
POLAND						1	13		1		2		1	3			2	5				1	3
RUSSIA		3			1	10	15			2	3		2	3				2				2	21
SOUTH KOREA	1						2				3			1	2			1	2				5
SPAIN	1	1	2			26	10	2		4	1	4	2		5	2	1		1	1		7	14
SWEDEN		1			3	2	1		1	1			1				2	1		2		4	5
SWITZERLAND	2		6	2		7	15			6			2					1	2			1	10
TAIWAN											1											1	4
UK	1	3		1		11	14	1	4	2	8	4	4		1	2		7	4	1	1		17
USA	5	13	4	34	4	31	46	6	12	7	43	9	5	13	3	21	5	14	5	10	4	17	
N of Co-authorships	20	36	24	56	18	176	211	17	35	66	88	18	42	53	32	64	17	84	24	54	6	86	311

Fig. 1. Country co-authorship matrix

Differences in application

Along with studying the emergence of a novel technological field goes the question to which degree scientific findings have been applied already. In this context, bibliometric data as such and on its own is of little help. Thus we also look at patent data in order to compare publishing with patenting activity of countries. However, it should be stressed that one cannot establish any causal links between papers and patents. But referring to earlier work by *Narin* and his colleagues[14] on patented technology in the USA and the underlying science base, one could expect that a country that has high paper counts does well in patenting too, especially in a science-based field such as nanotechnology. In their study *Narin* et al. could show that the within-country connection between basic science and applied technology is especially profound in the highly scientific areas of technology. A recent study by the same group underpins these findings.[15] By tracing the rapidly growing citation linkage between US patents and scientific papers, *Narin* et al. could show a strong national component, with each country's inventors preferentially citing papers authored in their own country, by a factor of between two and four.

We applied a similar search strategy to US patent data as we did earlier on in our bibliometric search mostly using the terms *Braun* et al. chose too.[16] Thereby we found more than 2000 nano-patents for the search period 1990-1997. Table 6 gives an overview of patenting activities in relation to publications. It contains publication and patent counts for countries with patents held in nanotechnology.

As for the assumption, our data is inconclusive. On the one hand, we found some proof for the notion that countries which are big in publications are also big in patenting. At least the top five countries are the same and this even in the same order.[17]

On the other hand, we can show that there are countries that publish and patent in different manners. For instance, small industrialized countries, such as Norway and Finland, and, with Taiwan, also newly industrializing countries seem to achieve exceptionally good science-technology ratios, implying big in papers does not necessarily mean big in patents too. This leads to the question: What are the underlying factors for these differences in publishing and patenting?

Table 6
Patenting activities in relation to publications by country

Country	No. of publications 1988-96	No. of patents 1990-97	Publications/ Patents
USA[a]	2062	1636	1.26
Japan	649	150	4.33
Germany	547	84	6.51
France	505	68	7.43
UK	249	34	7.32
Switzerland	142	15	9.47
Taiwan	39	15	2.60
The Netherlands	96	12	8.00
Italy	148	10	14.80
Australia	51	6	8.50
Sweden	52	5	10.40
Belgium	67	4	16.75
Finland	20	4	5.00
Ireland	20	3	6.67
Norway	4	3	1.33
Denmark	45	2	22.50
Spain	162	1	162.00
Hong Kong	11	1	11.00
Total	4869	2053	2.37

[a] Due to the use of US patent data, the results for the US are deterred and should not be overestimated.

It should be noted that the simple relation of publications and patents we used is too crude a measure to make reliable statements about a connection between patenting and publishing activities of countries. It is meant as a first step to get an overall idea of what is going on. For more reliable results, one needs to go to the patents themselves and look at the extent to which they cite domestic scientific papers.

Conclusions

Our bibliometric study has raised a number of questions. We could show that the share of boundary-spanning, interdisciplinary and interfield publications is exceptionally high and still growing. This makes one wonder why nanotechnology is interdisciplinary to such an extent and why this trend seems to continue. Is it a typical phenomenon for emerging technologies? Is it because science is developing more rapidly in areas that are carried out in an application context, as *Gibbons* et al.[18] suggest? Another interesting question is what are the reasons for the varying developments of the different disciplinary fields? An analysis of citation frequencies might help identify some breakthroughs as explaining factors.

Our second major finding was that countries follow different patterns of collaboration. Some countries tend to have bilateral relations while others collaborate with a much larger array of nations. Why? Are there some historical or social reasons? Are there any multi-country projects that stimulate links between participating countries? Does the amount of international collaboration has any effect on domestic cooperation?

Finally our results from the comparison of publication and patenting activities indicate differences in the application of science between countries. Smaller countries, industrialized as well as newly industrializing did exceptionally well. Thus: What are the underlying factors for these differences? Is size the explaining factor here? Or do differences between the national innovation systems play the decisive role? A comparison of countries' science bases and endowments with high-technology enterprises would be interesting here.

The answer to those questions, however, won't be entirely a bibliometric one. We just started mapping a radically new, emerging technology on the macro-level mostly looking at countries as unit of analysis. But the questions raised require a more detailed analysis on a less aggregated level. Finding answers why nanotechnology is so interdisciplinary, why there are differences in collaboration patterns as well as science-technology transformation, requires an analysis using also other types of data. Still, a closer investigation and disaggregation of bibliometric data may come up with additional findings. Especially looking at citations of scientific papers in patents seems to hold some promise.

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   '(...) an increasing number of methods which are used to build structures smaller than the finest structures in current silicon chips, yet larger than individual atoms. This implies a scale from 1 nm to 1000 nm.'
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11. M. S. MEYER, *Nanotechnology and its Industrial Applications,* Wuppertal, W.WIS, 1996.
12. Search terms used by *Braun* et al. as follows (all terms searched begin with nano):
    ~crystalline, ~structure, ~particle, ~scale, ~composite, ~tube, ~crystal, ~gram, ~meter-Size, ~phase, ~cluster,~size, ~capsule, ~crystallite, ~sphere, ~flagellate, ~metric, ~filtration, ~lithography, ~fabrication, ~indentation, ~technology, ~colloid, ~porous, ~wire, ~bridge, ~crystallization, ~tubule, ~electronics, ~vid, ~particulate, ~tribology, ~foam, ~diffraction, ~tip, ~aggregate, ~crystallized, ~flare, ~material, ~dispersed, ~filament, ~powder, ~rheology, ~architecture, ~layer, ~lithographic, ~channel, ~device, ~electronic, ~fiber, ~granular, ~heterogeneous, ~meter-Thick, ~peptide, ~space, ~-Y-TZP/Al2O3, ~droplet, ~feature, ~gold, ~grained, ~mechanics, ~multilayer, ~pore, ~probe, ~whisker, ~analysis, ~ball, ~cavity, ~characterization, ~column, ~constriction, ~disperse, ~dispersion, ~electrode, ~fibrillar, ~manipulation, ~precipitate, ~radian, ~system, ~technique, ~template, ~topography, ~world, ~analytical, ~band, ~cell, ~cermet, ~chemical, ~chemistry, ~coll, ~crack, ~cyrstalline, ~diamond, ~dissection, ~domain, ~engineering, ~friction, ~grain, ~granule, ~hardness, ~heterostructure,

~laminate, ~layered, ~machined, ~mechanical, ~metal, ~meter-Particle, ~meter-Thickness, ~molecular, ~photonics, ~physics, ~porosity, ~processing, ~replica, ~rod, ~science, ~titanate, ~twin, ~vision, ~wear, ~-AMP, ~-Mg2Si, ~-NMR, ~-Na-15, ~composite, ~-SnO2, ~-Tin, ~-ZrO2, ~-object, ~-optical, ~amorphous, ~anatomy, ~anodization, ~apatite, ~battery, ~body, ~building, ~cage, ~capillarity, ~capsular, ~carbon, ~carrier, ~catalysis, ~ceramics, ~climate, ~compound, ~conductor, ~cone, ~construction, ~contact, ~crystal-Doped, ~cube, ~cyclitic, ~deformation, ~dimension, ~dimensional,~disk, ~dislocation, ~displacement, ~drop, ~droplet-ABA, ~dynamical, ~elastohydrodynamics, ~electromechanical, ~electron, ~element, ~encapsulated, ~environment, ~equivalent, ~etching, ~fabricated, ~fibril, ~filtered, ~gate, ~gauge, ~glass, ~heterogeneity, ~heterotrophic, ~hole, ~inclusion, ~ionics, ~junction, ~kinematics, ~laminated, ~lithographically, ~machine, ~machining, ~magnetism, ~mask, ~matrix, ~mechanism, ~mental, ~meric, ~meter-Structure, ~meter-T, ~meter-Thin, ~meter-Width, ~metersized, ~modification, ~optics, ~pattern, ~pinhole, ~pipe, ~pit, ~polar, ~polyhedra, ~porous,~positioner, ~precipitation, ~programmed, ~reaction, ~reactor, ~rheological, ~roughness, ~scaffolding, ~scatterer, ~sled, ~slider, ~solid, ~source, ~spacing, ~spectroscopy, ~strain, ~strip, ~subharmonics, ~surface, ~texture, ~textured, ~thin, ~tool, ~trace, ~tubue, ~welding, ~word.

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16. The patent data were retrieved from the US patent data abstract file #25 via Dialog based on the keywords used for article retrieval plus a limited number of other expressions relevant. The search terms were as follows (all terms searched begin with nano):
    ~crystalline?, ~filter?, ~illumination?, ~inclusions?, ~indentation?, ~laminate?, ~layer?, ~lithography?, ~matrix?, ~mechanic?, ~meric?, ~meter?, ~metes?, ~metr?, ~mhase?, ~mmeters?, ~modification?, ~mole?, ~mters?, ~osized?, ~particles?, ~particulates?, ~perm?, ~piqment?,~polyhedron?, ~por?, ~powder?, ~probe?, ~program?, ~rom?, ~sampling?, ~scal?, ~sequencer?, ~shell?, ~sized?,~slider?, ~sol?, ~sphere?, ~sponge?, ~store?, ~structur?, ~substituted?, ~substrate?, ~suspensions?, ~technology?, ~titanate?, ~tube?, ~tubul?, ~units?,~whiskers?, ~wire?
17. Institutions and individuals from China and Russia do not hold any US patents yet. This is why they are neglected here.
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