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NEWS AND OPINIONS

The nanotechnology race between China and the United States

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Summary It is generally agreed that the United States National Nanotechnology Initiative (NNI) has significantly influenced global nanotechnology development since its inception in 2000. The far-reaching impact of NNI and nanotechnology development, as evidenced by publications in high impact journals, has been rising rapidly over the last 10 years. Recently, the global nanotechnology community witnessed China's ascent in nanotechnology. With increased governmental funding and improved research infrastructure, China has made significant advances and currently has the fastest growing nanotechnology publications and related industrialization. On the one hand, the Chinese government, like the American government, continues to build and support a fertile nanotechnology community. On the other hand, efforts appear less organized in the European Union. Although the gap in nanotechnology impact between the USA and China has narrowed significantly over recent years, the two countries have evolved with their own research focuses. Yet, China is still left behind American nanotechnology in terms of average citations per papers and publications in high-impact journals. It is hopeful that competition and collaboration between the two countries in this field will positively advance the global nanotechnology development.

The art and politics of nanoscience and nanotechnology

Before the dawn of the new millennium, the then President of the USA Bill Clinton was invited by Science magazine to write an editorial. In the one-page piece entitled ''Science

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in the 21st century'', he wrote ''Imagine a new century, full of promise, molded by science, shaped by technology, powered by knowledge. We are now embarking on our most daring explorations, unraveling the mysteries of our inner world and charting new routes to the conquest of disease'' [1]. In 2000, the American government firmly kicked off its significant and influential National Nanotechnology Initiative (NNI) program after integrating all resources from Federal agencies, including National Science Foundation, Department of Defense, Department of Energy, Department of Health and Human Services (NIH), National Institute of Standard Technology (NIST), National Aeronautics and Space Administration (NASA), Environmental Protection Agency (EPA), Homeland Security, United States Department of Agriculture (USDA), and Department of Justice.

The NNI established four goals: (1) to advance a world-class nanotechnology research and development program; (2) to foster the transfer of new technologies into products for commercial and public benefit; (3) to develop and sustain educational resources, a skilled workforce, and supporting infrastructure and tools to advance nanotechnology; and (4) to support responsible development of nanotechnology. The NNI significantly pushes nanotechnology research forward. In 2006, the prominence of nanotechnology research began to exceed medical research in terms of publication rate. That trend appears to be continuing as a result of the growth of products in commerce using nanotechnology and, for example, five-fold growth in number of countries with nanomaterials research centers. The ''nanoscience and nanotechnology'' subject category of the Journal Citation Report (JCR) published by Thomson Reuters has increased rapidly. Correspondingly, both impact factors (published by Thomson Reuters) and SCImago Journal Rank values (SJR; published by Elsevier's Scopus and powered by Google's PageRank algorithms) of journals in the nanotechnology subject category have increased rapidly [2]. The aggregate impact factor of nanoscience and nanotechnology has been rising at a breathtaking rate, compared with other subject categories, reaching the top 10 after 2011. The hype and hope of nanotechnology challenging many previously unimaginable goals are especially high now, and many believe in forthcoming breakthroughs in the areas of nanomaterial-based diagnostic imaging, complementation of diagnostic tools combined with therapeutic modalities (i.e., theranostics), or nanoencapsulation and nano-carriers of biotechnology products.

Today, it is estimated that total NNI funding, including the fiscal year 2014, is about $170 billion. Currently, there are more than 60 countries that have launched national nanotechnology programs [3]. Governments and industry have invested millions of dollars in research funding in this rapidly growing field. By 2015, approximately one quarter trillion dollars will have been invested in nanotechnology by the American government and private sectors collectively. The continuous strategic investment in nanotechnology has made the United States a global leader in the field.

Ten years ago, when AAAS celebrated the 125th anniversary of the journal Science, the magazine invited the President of Chinese Academy of Science (CAS) Chunli Bai to write an essay for its special section ''Global Voice of Science''. The CAS President Chunli Bai's essay, entitled ''Ascent of Nanoscience in China'' [4] described, in general, the then development of nanotechnology and nanoscience in China, and openly announced the government's ambition to compete with other countries in the field. In 2006, the Chinese government announced its Medium and Long-term Plan for the Development of Science and Technology (2006—2020), which identified nanotechnology as ''a very promising area that could give China a chance of great-leap-forward development''. The plan introduced the new Chinese Science & Technology policy guidelines, which were later implemented by the Ministry of Science and Technology (MOST) that operates Nanoscience Research as a part of the State Key Science Research Plans. So far the Nanoscience Research program has invested about 1.0 billion RMB to support 28 nanotechnology projects. All of these endeavors led to the recent significantly rapid rise of nanotechnology in China as evidenced by its publications, industrial R&D and applications in the field.

The rapid development of nanotechnology-based science and technology in China attracted worldwide attention including from Demos, one of the UK's most influential think tanks. Led by Wilsdon and Keeley, Demos completed an 18-month study, interviewing many leading scientists and policy makers of 71 Asian organizations, including two well-known Chinese nanotechnology academics Dr. Chen Wang (the then Director of National Center for Nanoscience and Technology) and Academician Zihe Rao (Director of CAS Institute of Biophysics). After completion of the project, Wilsdon and Keeley published their findings in a book entitled ''China: The next science superpower?'' [5]. The authors wrote, ''China in 2007 is the world's largest technocracy: a country ruled by scientists and engineers who believe in the power of technology to deliver social and economic progress. Right now, the country is at an early stage in the most ambitious program of research investment since John F Kennedy embarked on the race to the moon. But statistics fail to capture the raw power of the changes that are under way, and the potential for Chinese science and innovation to head in new and surprising directions. Is China on track to become the world's next science superpower?'' Indeed, in recent years, China has emerged not only as a mass manufacturer, but also as one of the world's leading nanotechnology nations. Many nanomaterial-based semiconductor products come from China, and China dominates in the nanotechnology area of most-cited academic articles: the top eighteen out of the twenty scholars are of Chinese origin [6].

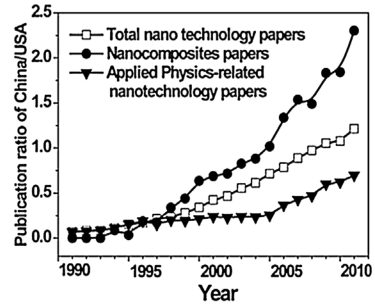
Changes in nanotechnology-related geopolitical landscape

With strong governmental and private sector supports, nanotechnology and nanoscience R&D has developed rapidly in both the USA and China. As shown in Fig. 1A, from 2003 to 2013, the USA led in the area of global nanotechnology publications in terms of the numbers of papers and their quality determined by the number of citations and H-index. China followed USA in the field. For instance, the total nanotechnology publications from USA were 160,870 with total citations of 4056,278, whereas, China published 154,946 papers with total citations of 2049,072. The quality of an article is usually judged by the number of citations

A

Country/area	Publications	Rank	Citations	Rank	Citations/ paper	Index	Rank	Comprehensive normalized value	Comprehensive rank
USA	160870	1	4056278	1	25.21	504	1	0.538	1
China	154946	2	2049072	2	13.22	270	2	0.373	2
Germany	47585	4	964074	3	20.26	268	3	0.140	3
Japan	51952	3	834534	4	16.06	230	4	0.136	4
Korea	41624	5	559763	7	13.45	204	7	0.101	5
France	33848	7	612111	6	18.08	211	6	0.094	6
UK	28688	8	650833	5	22.69	229	5	0.090	7
India	34040	6	359224	8	10.55	146	15	0.075	8
Italy	21769	9	341197	9	15.67	159	13	0.056	9
Spain	19885	12	338530	10	17.02	171	11	0.054	10
Taiwan (China)	20472	10	254650	13	12.44	135	16	0.048	11
Canada	16517	13	312993	11	18.95	174	9	0.047	12
Russia	19975	11	160170	17	8.02	112	17	0.040	13
Australia	13596	15	246811	15	18.15	151	14	0.038	14
Singapore	11888	16	262070	12	22.04	179	8	0.037	15
Switzerland	9767	17	249314	14	25.53	173	10	0.033	16
Holland	8941	19	225644	16	25.24	170	12	0.030	17
Iran	15629	14	106465	18	6.81	80	20	0.029	18
Brazil	9138	18	103736	19	11.35	101	18	0.021	19
Poland	8757	20	79053	20	9.03	89	19	0.018	20

B



C

Country	The most frequently-used nanotechnology keywords ranked by the author countries and their published frequency
USA	Nanoparticles, carbon nanotubes, nanocomposites, nanotechnology, nanostructures, nanotoxicology, self-assembly, nanomaterials, nanowires, drug delivery, mechanical properties, quantum dots, thin films, electrospinning, nanoindentation, graphene, polymers, atomic force microscopy, TiO_2, nanotubes, gold nanoparticles
China	Nanoparticles, nanostructures, carbon nanotubes, nanocomposites, microstructure, nanomaterilas, TiO_2, nanotoxicology, self-assembly, mechanical properties, composites, graphene, chemical synthesis, photoluminescence, ZnO, photocatalysis, luminescence, magnetic properties, gold nanoparticles, electrospinning, semicondutors
Germany	Nanoparticles, nanostructures, nanocomposites, carbon nanotubes, self-assembly, nanomaterials, thin films, nanowires, mechanical properties, nanotechnology, nanotoxicology, quatum dots, atomic force microscopy, nanotubes, microstructure, X-ray diffraction, silicon, nanoindentation, gold, TiO_2, polymers
Japan	Nanoparticles, carbon nanotubes, nanostructures, nanocomposites, self-assembly, nanomaterials, TiO_2, thin films, nanowires, microstructure, transmission electron microscopy, nanotubes, photoluminescence, ZnO, mechanical properties, composites, nanocrystals, gold nanoparticles, silicon, nanotoxicology

Figure 1 The leading countries that published most nanotechnology-related papers and their research focuses (2003—2013). (A) The publications and their quality analysis; the comprehensive normalized values are calculated by the weighted statistics. (B) Key research focuses of the top countries; The keywords are ranked according to their use frequency; (C) publication ratio of China to USA in the selected areas. When the ratio is <1, it indicates that USA is leading in the area, and vice versa. C also indicates that China produced more nanotechnology papers than USA did after 2010.

it receives, although other measures such as the number of downloads are becoming more accepted and used [2].

Based on the total publications and related citations, we used weighted statistics to calculate the all-inclusive normalized value W_k by using the following equation, and then ranked the top countries actively involved in nanotechnology research.

$$W_k = \sum_{i=1}^{2} \left(\frac{N_{ij}}{\sum_{j=1}^{C_i} N_{ij}} \right)$$

In the equation, we define the index i as 1 or 2, and N_{ij} as the publications of country J corresponding to the proposed index. By dividing N_{ij} by its sum up to C_i, we obtained the normalized value W_k for country K in comparison with that of country J. The weighted statistics (Fig. 1A) show that USA ranks number 1, followed by China, Germany, Japan, Korea, France, UK, India, Italy, Spain, Taiwan (China), and others. The EU countries are not too far behind in the field. Further analysis indicates that the number of nanotechnology-related publications increased from 23,957 in 2003 to 107,371 in 2013 world-wide (an increase of 4.48-folds). Among them, 3592 and 30.479 papers were contributed by China in 2003 and in 2013, respectively, that is an increase of 8.49 folds, which is about 2-fold higher than the global publication increase rate.

The bibliometric information presented in Table 1 shows twenty leading nanotechnology journals. The table shows that the USA is leading in nanotechnology research by far. The USA contributed 22,067 papers to the twenty journals from 2003 to 2013, whereas, China only published 3421 papers in these journals. If the analysis is limited to papers published in journals with an impact factor >20, the USA originated 1068 papers, followed by EU countries Germany (221), UK (193), France (149), and finally Japan (121). China only produced 76 papers with an impact factor >20, demonstrating that China has some significant hurdles to overcome to join the world's top countries in nanotechnology development. Interestingly, China is not lagging behind world leaders in all areas, for example, the gap between the USA and China is narrower in the field of nanomaterial research. As indicated in Table 1, publications from China in Advanced Materials, Advanced Functional Materials, and Angew. Chem. Int. Edit. are not much less than those from the USA. In fact, China is leading in nanocomposites,

Table 1 Key nanotechnology-related Journals and author countries (area) that contributed more papers to the journals (2003—2013).

Journals	IF (2013)	USA	China	Germany	Japan	UK	Korea	Italy	Taiwan (China)	India	France
Nat. Mater.	36.425	497	25	126	67	93	39	26	2	3	103
Nat. Nanotechnol.	33.265	571	51	95	54	100	41	34	11	6	46
Nano Today	18.432	120	53	22	6	22	14	7	8	2	5
Adv. Mater.	15.409	1615	1035	499	373	282	454	129	100	50	184
Angew. Chem. Int. Edit.	11.336	1090	705	678	361	300	254	97	43	67	176
Nano Lett.	12.940	4445	592	776	324	356	378	181	98	32	347
ACS Nano	12.033	2524	747	445	252	300	381	170	128	47	215
J. Am. Chem. Soc.	11.444	3887	968	542	765	426	324	229	82	80	321
Nat. Commun.	10.274	272	95	79	69	64	47	21	8	6	41
Adv. Funct. Mater.	10.439	774	638	336	161	173	269	95	86	43	141
NPG Asia Mater	9.902	9	27	2	7	3	13	0	6	1	0
Nanotoxicology	7.336	116	28	36	11	54	7	27	6	15	20
Small	7.514	974	572	419	146	149	206	99	53	47	103
Nano Res.	6.963	195	231	27	25	14	20	9	8	14	17
Nanomend. Nanotechnol. Biol. Med.	5.978	268	74	37	18	29	22	27	13	73	18
Nanoscale	6.739	755	1398	193	172	179	219	144	100	152	142
Carbon	6.160	799	1155	219	451	202	306	130	147	106	268
Nanomedicine: Nanotechnol. Biol. Med.	5.978	345	63	36	19	83	18	44	13	52	33
Nanotechnology	3.672	2514	2212	651	543	557	854	306	516	362	469
Int. J. Nanomed.	4.195	297	458	45	45	35	53	49	62	71	26
Total	—	22,067	3421	11,127	5263	3919	3869	2675	1824	1490	1229

chemical synthesis, and photocatalysis research (Fig. 1B and C). Chinese scientists published 1712 and 1580 papers in chemical synthesis and photocatalysis (from 2003 to 2013), respectively. The numbers exceed those from India, South Korea, Japan, USA, France, Germany, UK and Italy combined, suggesting that Chinese researchers have evolved their own research focuses and strengths over the years. On the other hand, this fact may also indicate an overinvestment of resources in this area.

Table 2 shows the top 10 universities and institutes world-wide as well as those located within USA or China who contribute the most nanotechnology publications. It reveals that the authorship of China's nanotechnology publications is mostly concentrated in a small group of prestigious institutes and universities, reflecting the more centralized governance of China science, while authorship in the USA is more widely distributed. Indeed, the CAS possesses more resources than other competitors in China.

The geopolitical differences between the USA and China are also reflected in nanotechnology-related patent applications and industrialization. The numbers of nanotechnology-related patent applications to the US Patent and Trademark Office (USPTO), or the State Intellectual Property Office of China (SIPO) have increased from 405 in 2000 to 3729 in 2008 in USA, or from 105 in 2000 to 5030 in 2008 in China [7]. According to the China Patent Abstract Database managed by the SIPO, there were 30,863 nanotechnology patent applications from 1985 to 2009, and most of them were published after 2003. The central government has already built several state-level nanotechnology R&D incubators or bases, including the National Center for Nanoscience and Technology of China in Beijing, The State Engineering Research Center for Nanotechnology and Applications in Shanghai, National Institute of Nanotechnology and Engineering in Tianjin, Zhejiang—California International NanoSystems Institute, International Innovation Incubator of Nanotechnology, in Suzhou. In general, Beijing and Shanghai remain the two dominant nanotechnology centers, followed by Jiangsu and Zhejiang, reflecting the regional divergence of Chinese nanotechnology development [8].

The China—USA relationship is as compelling as it is complex. Approximately, one out of ten professionals in Silicon Valley's high-tech workforce is from mainland China [8]. In today's global economy, the two great countries compete with each other in nanotechnology in a parallel and compatible manner. Historically, the United States has led the

Table 2 Top Institutes in the world and in China and USA that produced the most nanotechnology-related papers.

Institutes in the world	Country	Publications (2003—2013)	Top institutes in USA and China	Country	Publications (2005)
Chinese Academy of Sciences	China	27,912	Chinese Academy of Science	China	2916
Russian Academy of Sciences	Russia	10,242	Tsing Hua University	China	749
Tsing Hua University	China	6,276	Nanjing University	China	534
CNRS	France	6,248	Zhejiang University	China	528
National University of Singapore	Singapore	5,593	University of Science &Technology of China	China	482
Zhejiang University	China	5,534	University of Illinois	USA	461
Nanyang Polytechnic	Singapore	5,197	University of California at Berkeley	USA	472
Indian Institute of Technology Madras	India	5,171	University of Texas	USA	419
Seoul National University	Korea	5,070	Peking University	China	400
Nanjing University	China	4,874	Jilin University	China	378
—	—	—	Shanghai Jiaotong University	China	367
—	—	—	MIT	USA	364

global high-tech and nanotechnology fields. However, the gap between USA and China in nanotechnology has narrowed significantly in recent years and American nanotechnology leadership faces challenges from all over the world. With improved investment in research infrastructure and funding, China is sustaining the fastest economic growth in the world. Citizens' participation in nanoscience and nanotechnology-related consensus conferences or stakeholder dialogues has become normal. This has not only had a significant impact on nanotechnology development in China, but also is democratically legitimate. Interest-based civil society interventions play an important role in the polycentric governance of nanoscience and nanotechnology to ensure that the related policies and regulations are made prudently after open argument and discussions [9]. It would be interesting to watch, debate and decide which type of governmental system, the centralized one-party or the almost equally-divided two-party system, can more efficiently and effectively utilize public resources to produce nanotechnology products that better serve their own taxpayers, and the worldwide community as well.

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