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POLICY ANALYSIS:

CHARTING NANO ENVIRONMENTAL, HEALTH, AND SAFETY RESEARCH TRAJECTORIES: IS CHINA CONVERGENT WITH THE UNITED STATES?

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Executive Summary

Despite China's recent entrance into the Nano Environmental, Health, & Safety ("EHS") field, China is currently the number two producer of Nano EHS research, following the United States. As is demonstrated in this paper, China is quickly gaining ground on the United States in a number of key Nano EHS research areas and looks to one day establish leadership positions of its own in these domains. China's escalating efforts to promote Nano EHS research, along with its rapid growth of research outputs in this field and increasing Sino-U.S. research collaboration in multiple research domains, raises the question: Is Nano EHS research in China developing a character of its own or is it following the path charted by the United States? Utilizing a unique dataset of global Nano EHS publications, this paper, focusing on the negative aspects of Nano EHS scholarship, compares American and Chinese Nano EHS research trajectories with a number of evaluative metrics. Research trajectories for both countries are charted via research intensity, measured in terms of location quotients, and research focus, measured in terms of absolute and percentage growth of top research keywords. The present analysis argues that China's rapid development in the Nano EHS domain can be characterized by a pattern of convergence to the path of the United States. Yet, China's state-led Nano EHS program is also a key driver of its own research direction, as evidenced by the dual development of research streams and national policy initiatives with evolving funding priorities. The policy implications for both countries are also discussed in the end.

U.S.- China Policy Landscape: Since Richard Feynman's seminal talk, "There is Plenty of Room at the Bottom," at the annual meeting of the American Physical Society in 1959, nanotechnology has gained worldwide momentum. Heralded as a promising new field, nanotechnology, an interdisciplinary discipline that involves manipulating molecular-sized materials to create new products and processes with novel features with nano-scale properties, is expected to heavily influence socio-economic development (Roco & Bainbridge, 2005; Zucker & Darby, 2007). Accordingly, many countries have prioritized nanotechnology on their national research agenda (Roco, 2005), including China and the United States (Tang & Shapira 2011). On the other hand, scientists and policymakers alike are increasingly recognizing the potential negative effects of this emerging technology. Over the last decade, concern relating to environmental, health, and safety issues in nanotechnology ("Nano EHS") have triggered an array of policy initiatives across a number of countries (Roco & Bainbridge, 2005). In the United States, the risk-conscious development of nanotechnology has been a key objective since the National Nanotechnology Initiative was established 2001. In contrast, Chinese research interest in Nano EHS is a more recent phenomenon, in spite of its early entrance into the field of nanotechnology (Shapira & Wang, 2009; Tang & Shapira, 2011).

China's efforts to promote nanotechnology research can be traced back to 1990, when the Ministry of Science and Technology launched the ten-year "Climbing-Up" project (Bai 2001, Tang, Wang, & Shapira 2010). Ten years later, the Chinese Academy of Sciences (CAS) scientists initiated a series of activities to identify and quantify the hazards resulting from exposure to manufactured nanoparticles and nanomaterials in 2001. Since then, China has hosted a series of workshops, conferences (e.g. the Xiangshan Science Conference), and research projects centering on this new field. Examples of such programs include two major five-year projects on the "Toxicological Effects of Carbon Nanomaterials" (2004-2008), the "Environmental Activity and Health Impact of Ambient Superfine Particles" (2006-2010) sponsored by the National Natural Science Foundation of China (NSFC), and the "Nano-safety Project on Health and Safety Impacts of Nanotechnology" under the National Key Basic Research Program of China (Chen, 2010; Zhao et al., 2008). These funding programs demonstrate shifting Nano EHS funding priorities from targeting on nanoparticles/nanomaterals study to a more balanced research portfolio related to overall environmental, health and safety issues.

The principal administrative body coordinating all national research activities in China is the National Steering Committee for Nanoscience and Nanotechnology. Its primary objective is to support significant research for technology commercialization and economic growth, rather than regulatory monitoring and risk governance. In contrast, the U.S. National Nanotechnology Initiative integrated both priorities from the beginning. This may partially explain the missing research element of nano EHS from Chinese scholarship in the early to mid 1990s. Due to intensive debates on nano risk governance in the United States and European countries, as well as a nanoparticle exposure accident in a Chinese paint factory (Song, Li, & Du, 2009), Chinese policymakers shifted focus to the risk management aspects of nanotechnology. China established its first National Lab for Bio-Environmental Health Sciences of Nanoscale Materials at the CAS's Institute of High Energy Physics (CAS-IHEP) in 2003 (Tang, Wang, & Shapira 2010; Gilbert 2009). China went to establish the National Technical Committee on Nanotechnology (SAC/TC279) to issue nanotechnology standards and raise the threshold of accessing nanometer silver antibiotic treatments in 2004. In 2006, CAS-IHEP and the National Center for Nanoscience and Technology (a research institute sponsored by the Chinese government) opened a joint Lab for the Bio-Environmental Effects of Nanomaterials & Nanosafety to identify the adverse effects of nanomaterials, to eliminate nanotoxicity, and to reduce the release of nanoparticles in manufacturing processes.

The Chinese government's advancement of Nano EHS research should be understood in the context of national S&T strategies on science-driven economic development. Topping the priority list of research areas, Chinese government targets on capitalizing nanotechnology EHS benefits in energy efficiency, pollution reduction, and health improvement, while minimizing the adverse effects on human organs and ecosystem degradation (Chen, 2010; Zhao et al., 2008). To harvest adequate public investment, nanotechnology commercialization should take occupational and health considerations into account. This helps explain why China's Nano EHS activities are conducted within and coordinated by the National Center for Nanoscience and Technology.

China's promulgation of Nano EHS research has led to a number of quantifiable results. After its first Web of Science-Science Citation Index (WOS-SCI) [1] publication on mitoxantrone-nanoparticle toxicity (Zhang et al., 1999), Nano EHS research in China has achieved remarkable growth. By the end of 2009, China's Nano EHS research program ranked second in global research publication counts, closely following the United States. China's rapid development in the Nano EHS field, as well as the increasing Sino-United States research collaboration in all research domains, raises the question: is Nano EHS research in China following the path charted by the United States or is it developing a character of its own?

To address this question, this paper develops a unique Nano EHS publication dataset from the United States and China and compares the country's respective development trajectories. Drawing on peer-reviewed journal articles from WOS-SCI, the authors have constructed Nano EHS datasets for the United States and China via three rounds of reduction: nanotechnology filters, EHS filters, and manual verification. The Nano EHS publications used in the present analysis are drawn from a larger dataset that was developed by Porter et al. (2008). The results of the latter search form what today constitutes Georgia Tech's global nanopublication dataset, which contains more than 750,000 records and spans 1990 to 2009. Applying a Nano EHS thesaurus as well as manually screening each candidate abstract record resulted in a dataset that consists of 485 American and 168 Chinese Nano EHS publications (Figure 1) exploring the potential safety, risk, and exposure issues in the nanotechnology research domain. For a more detailed description of the selection process see Note 1.

[1] www.isiknowledge.com

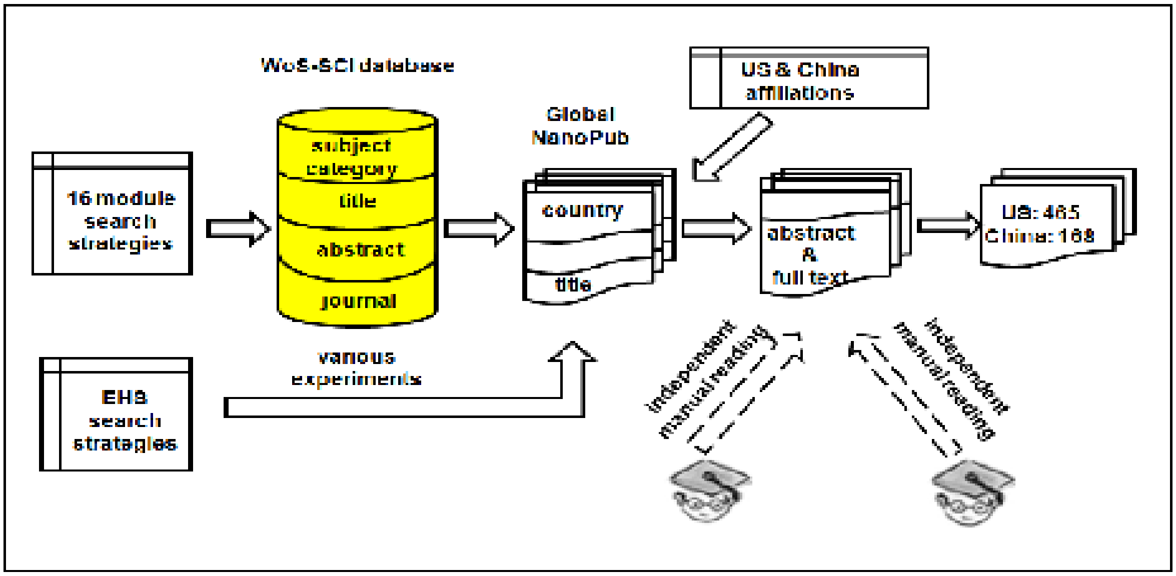

Figure 1: The Nano EHS Selection Process

Analysis of U.S.-China Nano EHS Research: First, we explore the research focus. Borrowing the notion of the location quotient (LQ), which is a measure of concentration between a local economy and a referent economy, Figure 2 graphs the Nano EHS research intensity dynamics for China and the United States over time (see Note 2). Although China is the number two producer of Nano EHS research, its LQ is consistently lower than what is observed for the period under consideration. By contrast, the research intensity of actual Nano EHS research in the United States over time is not only far above China's intensity, but also larger than would be expected from the global average (i.e. it is consistently greater than one). Despite these differences China and the United States share a number of common patterns in terms of their LQ dynamics. First, as reflected by increasing bubble size, both countries demonstrate upward trends in Nano EHS research. Moreover, if we connect the LQ dots of these countries we observe similar trend curves between them with a time lag of approximately seven years.

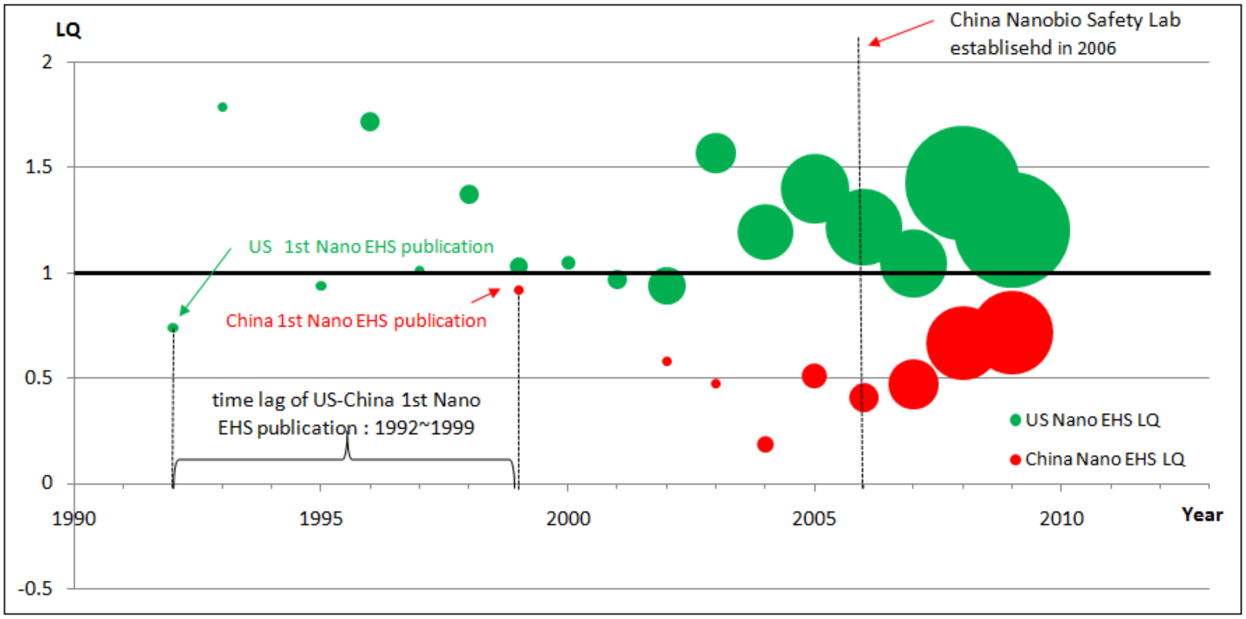

Figure 2: Dynamic Changes of Nano EHS Location Quotients: United States vs. China. The size of nodes is proportional to the counts of Nano EHS research papers.

Based on similarities in patterns of LQ development in both countries, it is tempting to conclude that China's EHS study followed the same trajectory as that of the United States. Before drawing this conclusion, however, we conducted a keywords analysis, based on the premise that keywords provide a surrogate for research interests within a country's Nano EHS program (see Note 3). Figure 3 lists the top 10 keywords, in terms of both absolute publication counts as well as percentage contribution to Nano EHS research, for the United States and China in the above examined period. Although the number of China's Nano EHS articles is only one third that of the United States, its top 10 Nano EHS keywords are identical to the top 10 for the United States. We note that, while the distributions of these (keywords?) are not identical across countries, they are notably similar. Figure 3 also shows that the emphasis on the negative effects of nanoparticles and in vitro research on EHS are more pronounced in China than in the United States. Next, we consider the research focus-- development trajectories of these keywords over time.

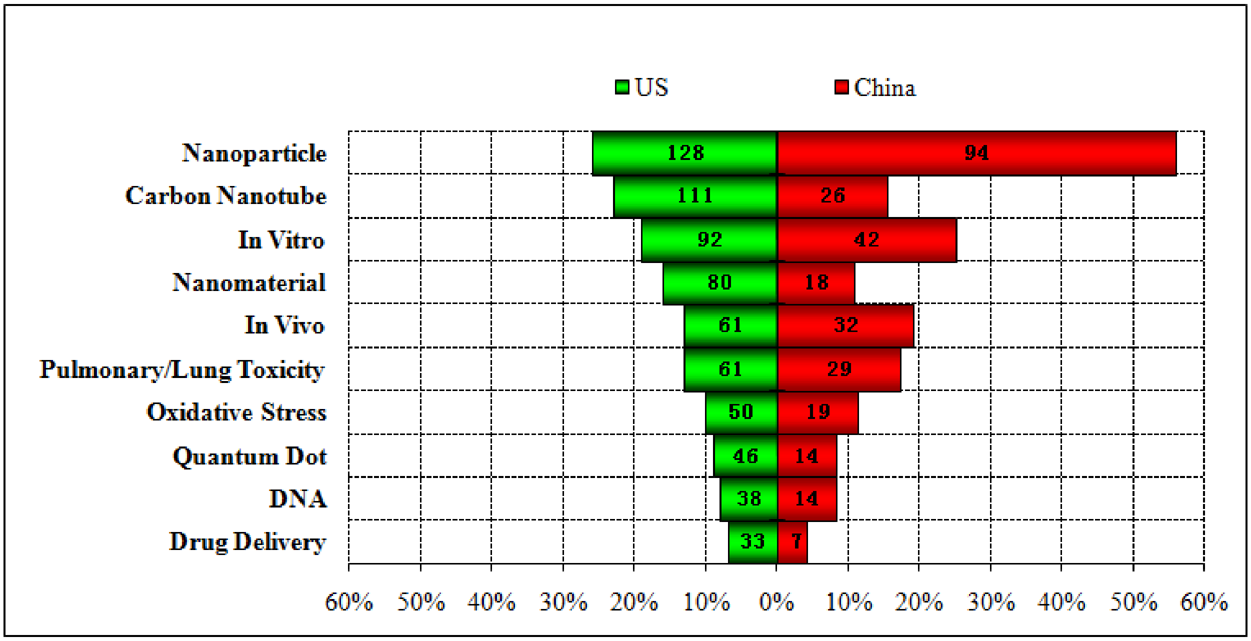

Figure 3: Top 10 Nano EHS Keywords for the United States and China

Figure 4 contrasts the emergence of top keywords over time in China against the United States. In order to smooth out year-to-year fluctuations, a three-year moving average is adopted for the time window. We observe that China's Nano EHS program generally progresses from a singular research stream to a full-fledged research profile, meaning it shifted from a sole concentration on nanoparticles to a more balanced research profile. The composition of China's Nano EHS research is gradually diversifying. This is evidenced by the coverage of semantic areas: all top 10 keyword terms have appeared in each year's research articles since 2007. It should also be noted that, when compared to the United States, China's keywords demonstrate more variation with the passage of time. Dramatic changes in attention to certain research areas can be indicative of external influences, like a national research program. As indicated by the Punctuated Equilibrium Theory (Baumgartner & Jones, 1993), which provides an explanation for processes that are characterized by stability but experience occasional large-scale departures from the past, large shifts in research emphases may signal that Nano EHS in China is becoming increasingly driven by forces external to its community of scholars--namely, a national research agenda.

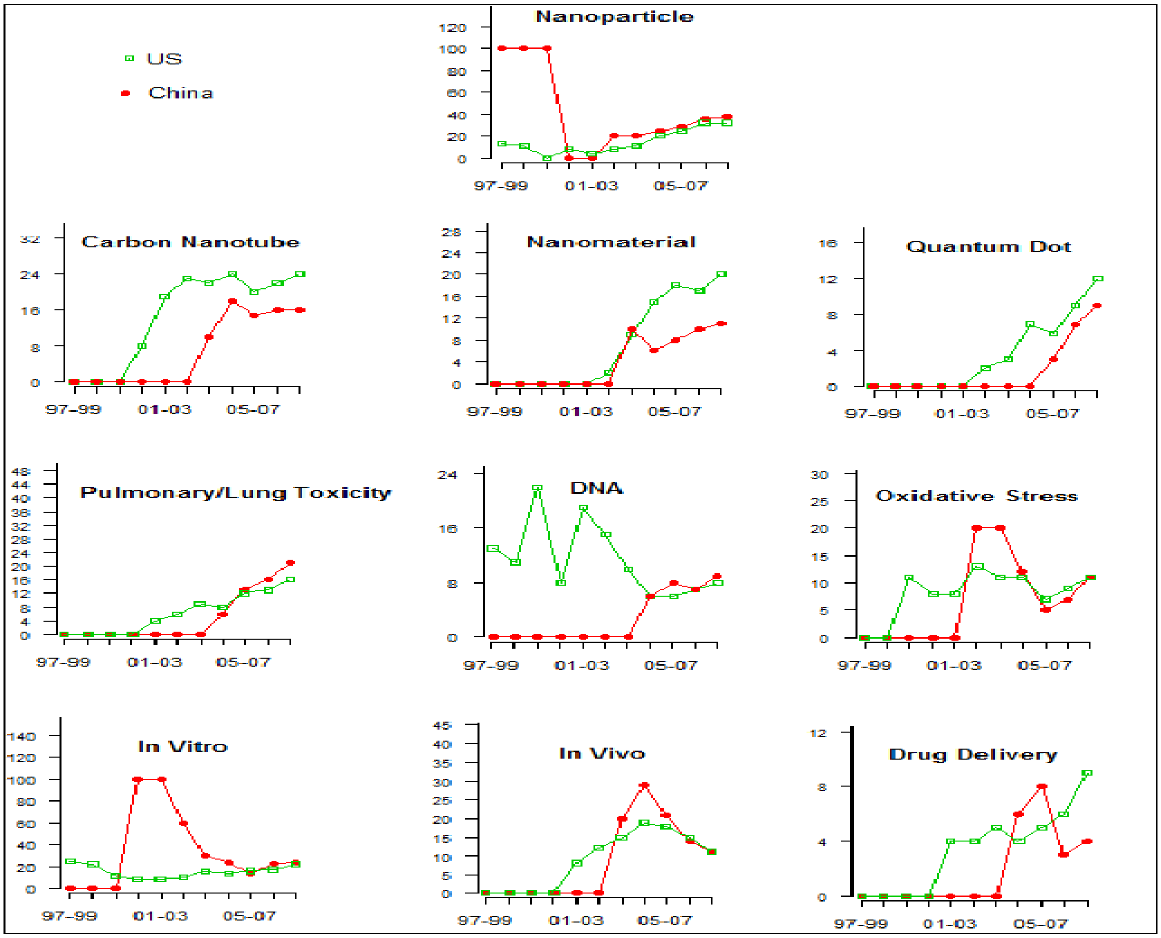

Figure 4: Growth of Top 10 Nano EHS Keywords for the United States and China. The X-axis represents the year; the Y-axis (%) represents the percentage of articles containing the keywords relative to the total number of Nano EHS publications for a given country within a given period.

A closer examination of individual keywords reveals a number of salient patterns. The first is represented by research topics on nanoparticles. China made its debut into the world of Nano EHS research in 1999, with an article that explored the adverse effects of nanoparticles on the liver (Zang, et al., 1999). Since then, Nanoparticle research has remained a hallmark of China's Nano EHS research program. As illustrated in Figures 3 and 4, the percentage of China's Nano EHS papers on nanoparticle research is consistently higher than what is observed in the United States. By contrast, China's Nano EHS research on carbon nanotubes, nanomaterials, and quantum dots (the 2nd row of Figure 4) demonstrate a similar development pattern as what is observed in the United States, followed by a brief time lag and smaller percentages. Another pattern, illustrated in row three of Figure 4, shows that China is quickly catching up with the United States and demonstrates the ability, at times, to surpass the United States (e.g. we see this in the pulmonary/long toxicity, DNA, and oxidative stress research domains). China's other Nano EHS research focusing on in vitro, in vivo, and drug delivery (the 4th row) shows a less stable development pattern than the United States (i.e. its keywords demonstrate more movement over time).

Conclusions: This paper has charted the Nano EHS development pathways for China and the United States by way of two indicators: research intensity, measured in terms of location quotients, and research focus, measured by the absolute number and the percentage of top keywords. Tracing China's Nano EHS research interests over time produces evidence that suggests an increasingly sophisticated mix of studies on Nano EHS. The similarities in the research focus of the United States and China (Figure 3), in addition to the trend of LQs (Figure 2), show that Chinese Nano EHS researchers are pursuing similar themes as their United States counterparts, which lends support to the convergence hypothesis.

On the other hand, the evolution of research topics (Figure 4) is consistent with China's Nano EHS program funding priorities. As discussed earlier, China's funding priorities on Nano EHS research have evolved over the last decade from a primary focus on nanoparticles and nanomaterials to a broader portfolio, including research on nano's biological and medical effects. Linking China's policy initiatives with its research performance shows that Nano EHS study parallels its evolving policy contexts and funding priorities for different time periods. The establishment of the National Laboratory for Biological Effects of Nanomaterials and Nanosafety (hereinafter "Bio-Lab") in 2006 was a noteworthy event for Nano EHS research in China: both research output and research intensity trend upward from this point (Figure 2 & 4). Not surprisingly, given the Bio-Lab's mission to promote research investigating the properties and health and safety effects of nanotechnology, rapid growth is particularly manifested by the research streams of in vivo, pulmonary/lung toxicity, and quantum dots (Figure 4). The connection between China's research topic evolution and state-led programs, along with its dynamic changes in research focus (Figures 2 & 4), as well as the fluctuating shifts of keywords, suggest that China's Nano EHS research is increasingly driven by its own evolving policy contexts.

Policy Implications: The above research yields policy implications for both China and the United States. Given their simultaneously strong growth in Nano EHS research output, both China and the United States stand to gain via mutual collaboration. While the present analysis finds evidence supporting convergence, we note also that each country has areas of specialization. Sharing and collaborating on research in which a given country has exhibited relatively faster growth and specialization will serve to stimulate the aggregate pace of Nano EHS diffusion for both countries. Because progress in the Nano EHS domain facilitates progress in other nano domains, as well as protects consumers and the environment, the argument can be made that a cooperative, instead of competitive, arrangement is in the best interest of both countries.

On the other hand, international scientific collaboration can represent a "double-edged sword" at times. From China's perspective, a shifting research agenda triggered by collaborating with American peers may suggest that Nano EHS development in China will advance, but it may also indicate passiveness among Chinese researchers when it comes to choosing research topics. Convergence among research streams can undermine the efficient utilization of R&D investment for China's own needs. This problem is particularly acute given the weak linkage between science and industry in China, a deep-rooted problem of the Chinese national innovation system. From this viewpoint, it is debatable whether pursuing state-of-the-art research topics is fruitful or whether it "tilts research away from those [is there a good missing here?] relevant for national development" (Baty, 2009; Liu etc 2011).

From the side of the United States, concerns have grown that China's enhanced research capabilities may pose a challenge to American technological leadership. For example, a major report by the Committee on Prospering in the Global Economy of the 21st Century concludes that American global leadership in science and technology is declining as foreign nations—especially China and other Asian countries—rapidly develop their national science and innovation systems (2007). Section 1340 of the 2011 spending legislation explicitly forbids federal funds to be used to "develop, design, plan, promulgate, implement, or execute a bilateral policy, program, order, or contract of any kind to participate, collaborate, or coordinate bilaterally in any way with China or any Chinese-owned company" in the National Aeronautics and Space Administration (NASA) and the White House Office of Science and Technology Policy (OSTP) (Clemins, 2011; Mervis, 2011). The cut-off of funding is, interestingly enough, applicable only for scientific exchanges between the United States and China in NASA and OSTP. The impact of this change on the course of future scientific diplomacy remains to be seen.

In summary, our analysis suggests that China's rapid development in the Nano EHS domain can be characterized by a pattern of convergence with the development path of the United States. This outcome is consistent with the Leader-Laggard Model of diffusion, in which a first-mover acts as a pioneer in the pursuit of a given policy agenda, and other actors, after observing the leader's behavior, follow suit (Walker, 1969). In addition, the present study finds that China's state-led Nano EHS program is also a key driver of its own research directions, as evidenced by the dual development of research streams and national policy initiatives with shifting funding priorities. Since convergence would imply that the United States is the leader and China is the laggard, whereas following state funding priorities would imply that China is assuming its own position of leadership, we conclude, cautiously, that China's nascent EHS research program has exhibited early convergence with the United States, but may slowly come to develop trajectories of its own over a longer time horizon.

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Notes

Note 1: Following various experiments, a thesaurus that identifies potential adverse effects of Nano EHS research is applied to Georgia Tech's global nanopublication dataset publications, yielding 2,758 candidate Nano EHS records. For more details on the construction of this thesaurus please refer to Youtie et al. (2011). Following their typology, only Nano EHS research articles that raise negative concerns are included for analysis. Those publications that were authored by an American (841 records) or Chinese (283 records) author were identified, and the remaining publications were dropped. The first and second author then read abstracts of each of these records and decided independently to further remove records that (i) did not clearly fall into the realm of nanotechnology, or (ii) considered EHS from a positive orientation. After cross-checking each other's reduction decisions it was determined that the authors concurred on more than 90% of the records that were dropped. The resulting dataset consisted of 485 American and 168 Chinese Nano EHS publications.

Note 2: In economic base analysis, location quotient is often used as an indicator of concentration by comparing the importance of a specific sector between a local economy and a reference economy. Mathematically, LQ is defined as:

$LQ_{i,t} = \left(\frac{NanoEHS}{Nano}\right)_{i,t} / \left(\frac{Global\ NanoEHS}{Global\ Nano}\right)_t$, where i represents either China or the United States, and $t \in \{1990, 1991, \ldots 2009\}$

If the $LQ_{i,t} > 1.0$, it indicates that the actual Nano EHS research in country *i* at year *t* is larger than would be expected from the global average. Conversely, an $LQ_{i,t}$ less than 1.0 suggests that the country shows less Nano EHS concentration within its nano research enterprise than the average.

Note 3: The composite set of key terms & phrases consists of three merged fields: 1) keywords submitted by the author i.e. "keywords author"; 2) keywords from cited titles i.e. "keyword plus"; and 3) title phrases extracted by natural language processing (*NLP*) from our Nano EHS publication dataset. Then, a set of high frequency, content-rich, nano keywords are derived (e.g. by grouping and consolidating term variants) and validated by hard nanoscientist. The resulting list was cleaned using VantagePoint text mining software.[2] A matrix of keyword frequency by year was generated and graphed using R program, an open source software.

[2] www.thevantagepoint.com

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