Hearing on China's Pursuit of Next Frontier Tech: Computing, Robotics, and Biotechnology
Testimony before the U.S.-China Economic and Security Review Commission

State of Nanotechnology R&D in China: Implications for Future US Competitiveness

March 16, 2017

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This testimony was prepared by Patrick J. Sinko in his personal capacity. The opinions expressed are the author's own and do not reflect the view of Rutgers, The State University of New Jersey.

Nanotechnology is a transformative technology revolutionizing many areas including energy, defense, information technology, agriculture, environmental protection and healthcare. While there are more than 60 countries that have launched national nanotechnology programs, the United States and China are the two leading countries engaged in nanotechnology research and development (R&D). It is important to understand the current status, drivers of R&D and commercialization, and market opportunities for nanotechnology development in the United States and China. Nanobiotechnology, nanorobotics and nanoinformatics, three nanotechnology subsectors that range in maturity status from near commercialization to emerging, will have an important impact on advancements in the field. A comparison of publications, granted patents, ecosystems, government and company investment, policies and regulations, technology transfer and commercialization, and industrial enterprise growth in nanotechnology-related fields reveals some marked asymmetries between the United States and China.

In order to address these issues, the testimony will be organized as follows:

1. Status of nanotechnology R&D in the United States.
2. China's major industrial policies supporting the development of the nanotechnology sector.
3. China's investment in nanotechnology R&D.
4. China's successes and challenges in nanotechnology R&D.
5. Summary of key points and recommendations for congressional action.

1: Status of Nanotechnology R&D in the United States.

Typically any discussion regarding nanotechnology starts with defining a size range (1 to 100 nm), however, the importance and potential impact of nanotechnology relates to the distinctive material properties that begin to express themselves when bulk scale material is nanosized. Other physical properties such as shape, porosity and smoothness strongly influence the behavior of nanoscale materials. In addition to physical properties, the composition of the material and material properties also significantly impact behavior at the nanoscale. While nanotechnology Research and Development (R&D) focuses on developing novel products based on Engineered Nano Materials (ENMs) in areas such as diagnostics, therapeutics or even military/defense applications, the unique properties of nanotechnology-based products have introduced unexpected environmental and health and safety issues that will require consideration by scientists and regulators alike.

The National Nanotechnology Initiative (NNI) is a multi-agency program established in 2000 that coordinates federal nanotechnology-related Research and Development (R&D) activities and related budget and planning processes to advance the field of nanotechnology across the United States. The NNI, the world's first national nanotechnology program, is comprised of 20 federal departments and independent agencies and commissions that invest in nanotechnology R&D and provide oversight. The NNI is coordinated within the White House through the National Science and Technology Council (NSTC), a Cabinet-level council under the Office of Science and Technology Policy. The Nanoscale Science, Engineering, and Technology (NSET) subcommittee of the NSTC, which is composed of representatives from participating agencies, coordinates planning, budgeting, implementation and review.

The vision of the NNI is "a future in which the ability to understand and control matter at the nanoscale leads to a revolution in technology and industry that benefits society."[1] To realize its vision, the NNI has established four goals:

- advance a world-class nanotechnology R&D program;
- foster the transfer of new technologies into products for commercial and public benefit;
- develop and sustain educational resources, a skilled workforce, and a dynamic infrastructure and toolset to advance nanotechnology; and
- support responsible development of nanotechnology.[1]

The NNI does not have centralized funding; rather, funding is provided directly through collaborative efforts by NNI member agencies that include the National Science Foundation (NSF), National Institute of Health (DHHS/NIH), Department of Energy (DOE), Department of Defense (DOD), and National Institute of Standards and Technology (NIST). Each agency allocates its nanotechnology R&D budget into categories of investment called Program Component Areas (PCAs) based on its needs and interests. The five PCAs are: (1) nanotechnology signature initiatives (NSIs); (2) foundational research; (3) nanotechnology-enabled applications, devices, and systems; (4) research infrastructure and instrumentation; and (5) environment, health, and safety. The NSIs are designed to focus on areas of national priority through interagency coordination and collaboration to facilitate faster translation from basic research activities to commercial applications. Current NSI priority areas include sustainable nanomanufacturing, nanoelectronics, nanotechnology knowledge infrastructure (NKI); sensors, and water sustainability.

The NNI has invested approximately $24 billion in nanotechnology R&D since 2001. Plotted in **Figure 1** is the inflation-adjusted total funding appropriation to the NNI since its inception. NNI funding by Congress gradually increased from FY2001 and reached its peak of $1.9 billion in FY2010. However, after the Department of Defense drastically reduced their investment (by $256 million) in FY2013, total NNI funding has not exceeded $1.5 billion. For FY2017, the Federal budget provides approximately $1.443 billion for nanotechnology R&D, which is 25% less than NNI funding for FY2010.[2] Under President Trump's FY2018 budget proposal, the spending on basic science would shrink by an additional 10.5%.[3] If a 10.5% reduction occurs, the inflation-adjusted NNI appropriation would be the lowest since 2004.

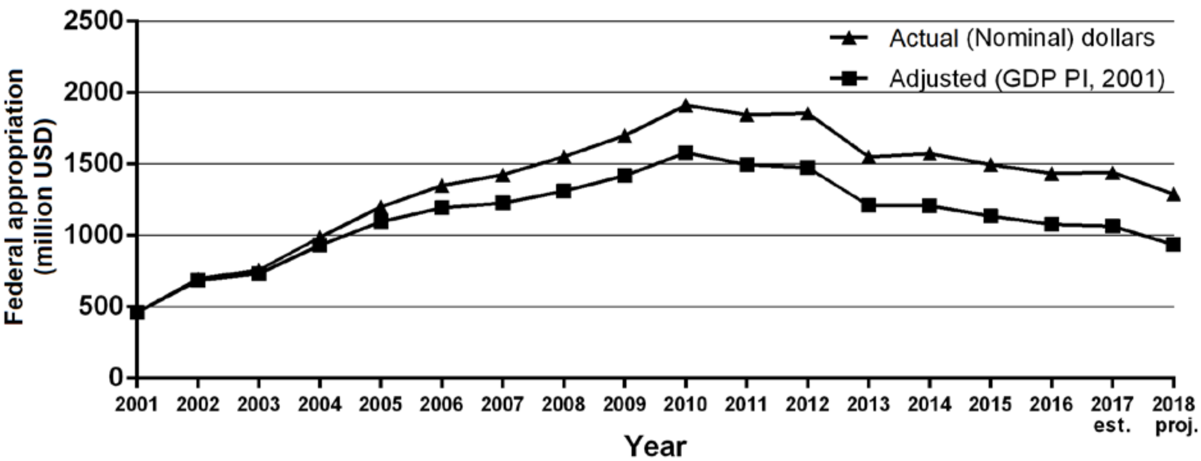

Figure 1. NNI funding, FY2001-18. Appropriations were inflation-adjusted to 2001 dollars to demonstrate real purchasing power. The GDP price index was used to make the adjustment. 2009 figures do not include American Recovery and Reinvestment Act funds ($510 million). (Source: reference 2)

The NNI has already made significant scientific and commercial impact thanks to the R&D activities of ~1200 companies, universities and government laboratories that have introduced nanotechnology into about 750 products. For example, scientists funded by the DOE's Office of Energy Efficiency and Renewable Energy Vehicle Technologies Program invented a new lithium-ion battery technology that incorporates integrated electrode structures at the nanoscale, thereby improving battery energy and efficiency.[4] Single-cell biology was a new area when the NNI was launched, but now it is "one of the most rapidly evolving assay biotechnologies."[5] Development of nanoscale sensors will also enable healthcare providers to detect and treat diseases at the molecular level. The NNI provides public access to the long list of achievements in nanotechnology online.[6]

Moving forward, the NNI has expanded its focus from investments in fundamental research to technology transfer that can promote the commercialization of nanotechnology-enabled products. For foundational research, the NNI continues to invest in the five NSIs. In 2016, a new NSI, *Water Sustainability through Nanotechnology: Nanoscale Solutions for a Global-Scale Challenge*, was launched to ensure water quality and supply.[1] To encourage the transfer of nanotechnology inventions from the laboratory to the commercial marketplace, NNI agencies sponsor a number of programs to drive the process. In 2016, the Nano Startup Challenge in Cancer (NSC^2) was introduced. The NSC^2 is a partnership among multiple government institutes and companies that used crowdsourcing to recruit talent across the country and around the world to foster the commercialization of cancer nanotechnology inventions.[7] Another example of public-private partnership is the Nano-Bio Manufacturing Consortium (NBMC) supported by the Air Force Research Laboratory. The NBMC has the goal of creating an industrial nano-bio ecosystem of suppliers, integrators, and end-users.[1]

The merging of multiple technologies into more complex systems has led to a variety of nanotechnology subfields. Three important areas of US nanotechnology development, nanobiotechnology, nanorobotics and nanoinformatics, where the US is the world leader will be highlighted to illustrate the convergence of technologies with nanotechnology and their implications. On the one hand, nanobiotechnology is the most mature of the three subfields that will be highlighted and, as such, there is an increased emphasis on translation and commercialization. Nanoinformatics, on the other hand, is an emerging field of great importance that will play a critical future role in nanotechnology opportunity and threat assessment.

Nanobiotechnology

In his book, Ehud Gazit defines nanobiotechnology as the "applications of nanotechnology techniques for the development and improvement of biotechnological process and products."[8] The convergence of two different fields—biotechnology and nanotechnology—has inspired many investigators due to its potential for innovation and as a result, this fairly new field has expanded rapidly over the past two decades. Nanobiotechnology includes many scientific disciplines such as biopharmaceuticals, drug delivery, diagnostics and certain areas of specialty instrumentation. One area in which nanobiotechnology has the greatest potential for changing current paradigms is therapeutics, especially precision medicine. "Precision Medicine refers to the tailoring of medical treatment to the individual characteristics of each patient. It does not literally mean the creation of drugs or medical devices that are unique to a patient, but rather the ability to classify individuals into subpopulations that differ in their susceptibility to a particular disease, in the biology and/or prognosis of those diseases they may develop, or in their response to a specific treatment. Preventive or therapeutic interventions can then be concentrated on those who will benefit, sparing expense and side effects for those who will not."[9] Rather than a "one-size-fits-all" approach, nanobiotechnology will allow the use of

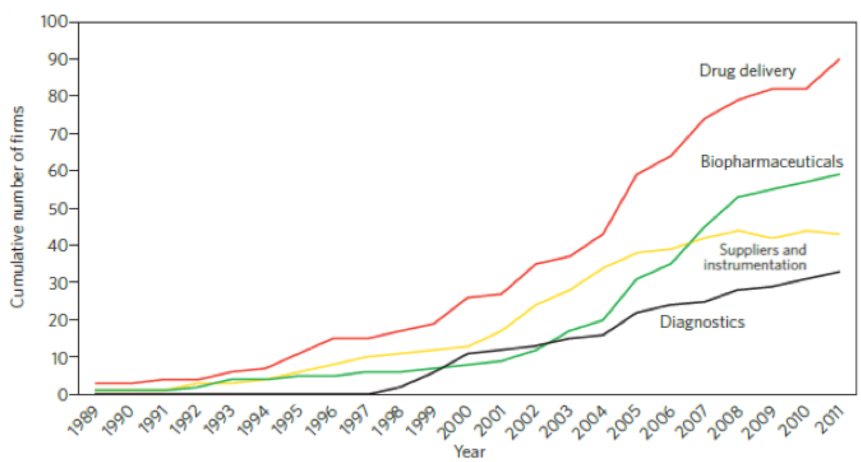

Figure 2. Cumulative number of companies in the US developing products in the four primary nanobiotechnology subsectors. (Reproduced from reference 10)

nanoscale techniques to develop more accurate diagnoses and more precise targeting, leading to effective treatments tailored to subpopulations of patients.

Nanobiotechnology is one of the more well-established nanotechnology subfields as a result of years of laboratory research and investment in universities and research institutes and by companies. Doxil®, one of the first successfully translated nano products that was approved by the FDA in 1995, encouraged the growth of new companies entering the bionanotechnology sector (**Figure 2**). Even though the suppliers and instrumentation subsector reached a plateau after years of rapid growth, the other subfields continued to increase, with the growth in the number of drug delivery startups being impressive. Interestingly, the plateau in the suppliers and instrumentation subsector was attributed to the emergence of a "dominant design"— in other words, a standard set of product features or technological attributes that becomes expected by the marketplace (for example, processes for nanoparticle synthesis)—resulting in a consolidation of firms in the industry.[10] At this stage of maturity, firms will refine their process attributes, such as cost reduction, and the market will start adopting the technology. Unfortunately, the translation of laboratory research in the nanobiotechnology sector to commercial products has been lackluster. As noted by numerous commentaries and articles, the timeframe for nanotechnology R&D has been much longer than originally expected reflecting two important nuances about nanobionanotechnology R&D. First, the research component has a much longer time horizon due to a general lack of a scientific foundation at the molecular scale. In addition, many unexpected phenomena have highlighted numerous potential environmental and health and safety issues. These potential issues have attracted significant attention by regulators, which further slows the introduction of nanobiotechnology products to market. While it is clear that the US is the world leader in nanobiotechnology R&D with approximately 60% of the companies[10] and the largest investment of any country in this sector[11], it is also clear that sustained investment in research is still required.

Nanorobotics

Micro/nanorobotics represent the next logical step forward after nanobiotechnology and is the result of the convergence of traditional robotics and nanotechnology. These small-scale robots function much like larger robots of today. Micro/nanorobots have been designed for targeted drug delivery, precision surgery, sensing, and detoxification.[12-16] They can move (locomotion), require an energy source for the "motor", have moving parts that can assist in surgery or take biopsy samples, etc. However, the challenges of miniaturization are numerous. For example, in order to move through blood vessels the robots can't be larger than a red blood cell (RBC), which moves freely through vessels. A RBC is about 6-8 microns in size. However, to move into tissues or tumors, the robot will likely have to be in the nanometer size range. At this size, regular molecular motions that occur (e.g., Brownian motion) will have a major influence on the locomotion of the nanorobot. As one paper recently concluded "Moving nanorobots from test tubes to living organisms would require significant future efforts. ... Operating these tiny devices in human tissues and organs that impose larger barriers to motion [than blood] requires careful examination."[12] From the perspective of the energy required for motion and the penetration into tissues it is clear that "smaller is better" and this is where the role of nanotechnology becomes clear. As such, significant technological developments will be required in the fields of nanotechnology and materials science. Although interest in micro/nanorobotics has grown significantly over the past decade the field is still in its infancy. Numerous significant challenges exist and translate into limited short-term potential for addressing healthcare issues. However, given the potential significance of micro/nanorobotics it is expected to become a vigorous area of research in nanotechnology in the future.

Nanoinformatics: Big Data, Artificial Intelligence and High Performance Computing.
"As multiple technology domains converge into more sophisticated systems, they link not only the benefits of those disparate technologies but also their risks."[17] Big Data, artificial intelligence and high performance computing are three emerging technologies that will play an important role in assessing potential opportunities and threats of nanotechnology products. Big Data generally refers to the handling and processing of large and/or complex data sets while artificial intelligence uses the data as well as pattern recognition and computational learning to generate new knowledge. High performance computing is required to accomplish these complex analyses. In fields like biotechnology, these approaches have already allowed "for leveraging research investments across multiple initiatives, facilitating trans-disciplinary translation of information, accelerating scientific discovery, and enabling faster risk assessment and commercialization of new technologies."[18] Similarly, large and complex data sets are inherent to the field of nanotechnology due to the wide variety of potential physicochemical properties as well as methods for fabricating, characterizing and evaluating nanomaterials. "This has led to diverse and rapidly emerging data in terms of materials, their interactions in environments, and across a broad spectrum of potentially relevant biological interactions."[18] For example, nanomaterials and their properties can be radically transformed upon release to the environment or exposure to the body. In other words, nanomaterials are highly dynamic in nature and there is an urgent need to understand, predict and control these changes. These profound and dynamic changes have significant implications on the potential efficacy, safety and toxicity of nanotechnology derived products in biomedical applications, environmental health and safety as well on national security and defense applications. To better understand nanomaterial behavior, the Nanoinformatics 2020 Roadmap was proposed and recently expanded: **"**Nanoinformatics is the science and practice of determining which information is relevant to meeting the objectives of the nanoscale science and engineering community, and then developing and implementing effective mechanisms for collecting, validating, storing, sharing, analyzing, modeling, and applying the information, and then confirming that appropriate decisions were made and that desired mission outcomes were achieved[…]."[18] In the future, nanoinformatics will be the primary tool for assessing the risks of applying nanotechnology as well as its potential benefits as well.

2: China's Major Industrial Policies Supporting the Development of the Nanotechnology Sector

In 1956, China established the Science Planning Commission consisting of more than 600 science and technology (S&T) experts to develop the first National Science and Technology Long-Term Plan (1956-1967) (the 12-year plan). The 12-year plan is credited with establishing the foundation for modern science and technology in China and had notable achievements including the development of China's nuclear weapons and space programs.[19] In the 12-year plan, the central government identified priority projects and provided resources to fund programs in those project areas.

In 2000, the National Steering Committee for Nanotechnology Development was established, which formally organized nanotechnology efforts at the national level. They were responsible for planning, coordination and providing advice on nanotechnology development. The committee was composed of scientists from universities, institutes and industry as well as administrators from the Chinese Academy of Sciences (CAS), Ministry of Science and Technology (MOST) and other government organizations.

Medium- to Long-Term Plan for the Development of Science and Technology (2006-2020) (MLP)
Modeled after the 12-year plan, China initiated the MLP in 2006. It became "increasingly obvious to [Chinese leaders] that those who own the intellectual property, and who control technical standards, enjoy privileged positions in, and profit most from, international production networks."[19] Therefore, the objective of the MLP was to make China an innovation oriented society by 2020. The MLP identified eleven priority S&T areas relating to national needs such as national defense and manufacturing. The MLP also identified eight areas of enabling technologies (referred to as "Frontier Technologies") and a series of priority projects in each area. Some examples of Frontier Technology areas included advanced manufacturing, biotechnology and new materials. The MLP calls for an expansion of basic research (i.e., developing new interdisciplinary areas as well as new disciplines) and identified 17 national megaprojects. The megaprojects are considered critical S&T project areas for elevating the core competitiveness of China on the world stage. They have involved substantial government investments and incentives for key technology and engineering projects with commercial applications.[20] Thirteen engineering megaprojects including prevention and treatment of major diseases such as HIV/AIDS and drug innovation and development and four science megaprojects including the development of nanotechnology were identified. Priority areas in nanoscience included research focused on nanotechnology in the fields of energy, the environment, information, and medicine.

As discussed in detail by Cao et al, the MLP addressed four critical problems in China's S&T development: (1) its record of innovation in commercial technology was weak, (2) the state of its technological capabilities failed to meet the nation's social needs, (3) its overall capability for defense-related technological innovation was less than impressive and (4) the state of science in China did not live up to expectations given the investments that were made.[19] Specific objectives of the MLP were to:

- Increase China's gross expenditures on R&D (GERD) to 2.5% or above of the gross domestic product (GDP);
- Strengthen domestic innovative capacity and reduce the dependence on foreign technology (to 30% or less); and
- Move China into the top five countries with respect to the number of patents issued annually to Chinese nationals and number of international citations of scientific papers.

Chinese government funding, technical support and regulation of nanotechnology comes primarily from the Ministry of Science and Technology, Chinese Academy of Sciences and the National Natural Science Foundation of China.

The Ministry of Science and Technology (MOST) - The Ministry of Science and Technology is responsible for determining China's science and technology (S&T) development priorities, establishing strategies, administering S&T programs, developing regulations and managing international relationships. In 2013, much of the expenditures were S&T program related with funded projects receiving about $4.5 billion USD.[21] "MOST funds approximately 15% of [China's] national S&T expenditures."[21] The two primary programs for disbursing R&D funding are the 863 and 973 programs.

The National High-Technology Research and Development Program (the 863 program)
The 863 program focused on industrialization. The goals of the 863 program were to boost China's high tech development, R&D capacity, socio-economic development, and national security. The 863 program can fund academic institutions, research institutes and domestic companies.

The National Key Basic Research and Development Program (the 973 program)
The 973 program focuses on basic science. Among the goals of the 973 program are to strengthen and support research on many major scientific issues concerning national socio-economic development including nanotechnology. Other important aspects of the 973 program deal with attracting, cultivating, and retaining highly qualified scientists, promoting international exchange and cooperation, and attracting high caliber individuals from overseas. The 973 program utilizes a 2/3 funding model whereby a decision is made for continued funding or to adjust priorities and funding level after the second year of a project is completed.

Among the MLP's science mega-programs, only the nanotechnology mega-program is supported by the funding mechanisms of both the 863 and 973 programs, further demonstrating the daunting breadth and complexity of inventing and commercializing nanotechnology-based products.

The National Natural Science Foundation of China (NSFC)
The NSFC is responsible for providing funding for fundamental basic research using the Chinese National S&T Guiding Principles. Applied research projects can also be funded especially if the project originates from a funded basic research project. Since the implementation of the MLP, the central government allocation to the NSFC has increased about 20% per year for the past ten years. Unlike other programs, the NSFC funds investigator-initiated (i.e., bottom-up) projects as well as strategy-driven (i.e., top-down) projects that emerge from established national priorities and needs.[21] About 45% of NSFC funding was in life sciences and health projects in 2013.[22] As a funding agency, the NSFC, which directly reports to the State Council, has broader reach since it also funds scientists who are not competitive for the 863 or 973 programs. The success rate of NSFC grant applications is about 25%, which is higher than the US National Institutes of Health average rate (18.3%) across all institutes and centers in FY2015.[23]

Chinese Academy of Sciences (CAS)
The CAS has played a key role in Chinese research since 1949. "CAS is headquartered in Beijing and comprises 104 research institutes, 12 branch academies, two universities and 11 supporting organizations in 23 provincial-level areas throughout the country. It both funds and performs research. [The CAS employs] 60,000 people across all of its institutes and universities, and [it had]

a budget of $6.8 billion [USD in 2013]."[21] The CAS provides experts for the selection committees of the 863 and 973 programs.

Recruiting Leading Academics and Overseas Talent

China recognized early on that there was a significant problem with the state of science in their country especially due to "brain drain."[19] To make up for this deficiency and revitalize the state of science in China, it made active efforts in training and recruiting back highly qualified human resources. Two of its most important efforts in this area are the Hundred Talents Program and the Thousand Talents Program. The Hundred Talents Program began in 1994 with the goal of attracting 100 outstanding scholars from within and outside of China by the year 2000. Over the years, the program recruited and cultivated over 2000 outstanding scientists.[21] In 2015, the program was redefined to support the recruitment of three specific categories of talents: academic director, engineering director, and young talents.[24] The Thousand Talents Program started in 2008 to attract overseas Chinese and top university talent from globally ranked universities. To date the program has attracted over 4200 people.

3: Current Status of China's Investment in Nanotechnology R&D.

Financial Support Provided to Chinese Companies, Institutes and Universities

R&D Intensity (RDI), a commonly used indicator of an economy's relative degree of investment in generating new knowledge, is calculated from R&D expenditures as a percentage of GDP according to the Organisation for Economic Co-operation and Development (OECD). From 1998 to 2005 China's RDI nearly doubled to 1.34%.[19] In 2015, China's RDI was 2.07%.[11] By comparison, the United States' RDI was 2.79% in 2015. An important aspect of the MLP is its reliance on the business sector. To reach the 2.5% target China will rely heavily on private industry R&D investing since government expenditures represent only 21.6% of overall R&D expenditures.[21] Projecting the current trend in China's investment in Gross Domestic Spending on R&D through 2020 (**Figure 3**) it appears that China may reach their RDI goal of exceeding 2.5% per year by 2020. However, many challenges remain that could impede the growth of the business sector investment such as the barriers between the R&D system and industry created by the less than optimal Intellectual Property Right (IPR) system and the inefficiencies of an immature technology transfer infrastructure remain. In addition, high technology research areas like nanotechnology that rely heavily on developments in the basic sciences may lag behind. This is a result of "China's emphasis on applied and product-development research[, which] means that funding for basic science remains low: only 5% of the country's total R&D [in 2014] is devoted to this, compared with 15–20% in other major OECD nations."[25]

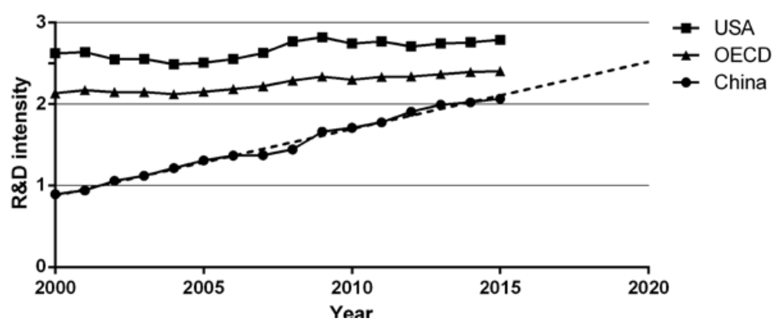

Figure 3. R&D intensity % (gross domestic spending on R&D as a % of GDP) for China, the United States, and OECD average, 2000-2015. (Source: reference 11)

In general, financial support for nanotechnology R&D in China comes from a variety of sources including the Central, provincial and local/city governments as well private industry and venture funds. In addition, companies benefit from incubators/accelerators, which in some cases are massive operations with all of the elements required for a nanotechnology ecosystem. This is particularly needed in China today as challenges with technology transfer and translation have been noted. For Universities and Research Institutes, nanotechnology funding for research is available from all of the programs and agencies previously described (i.e., MLP, MOST, 973, 863, NSFC and CAS). Funding for nanotechnology research in the US has been at or greater than $1 billion USD since 2004. Recent trends (i.e., since 2010) have demonstrated a steady and significant decline in US government funding of nanotechnology-related research funding (**Figure 1**). China, on the other hand, has seen dramatic increases in NSFC nanotechnology funding from $90 million USD in 2004 to about $600 million in 2014.[26] In 2012, US total spending (i.e., corporate and government) totaled approximately $2.2 billion USD whereas China's total was ~$1.3 billion USD.[26,27]

China's Innovative Capacity

The Chinese National Innovation index was developed by China in 2006 to track its progress in innovation by comparing itself to the top 40 countries that represent 98% of total global expenditures on R&D. The innovation index uses data from several sources among them the MOST, OECD, World Bank, World Intellectual Property Organization, World Economic Forum and others. The index is comprised of 30 qualitative and quantitative indicators in five groups (innovation resources, knowledge creation, enterprise innovation, innovation performance and innovation environment). The National Innovation Index Report 2015 was issued by the Chinese Academy of Science and Technology for Development (CASTED) on 29 June 2016. The top 10 in the ranking of the year were the US, Japan, Switzerland, South Korea, Denmark, Germany, Sweden, the UK, the Netherlands, and Singapore. China was ranked 18th in 2015, moving up one place from the previous year. In terms of the five main indicators that contributed to the overall ranking, China saw improvement from the previous year in innovation resources, knowledge creation, and enterprise innovation, whereas its innovation performance remained steady and innovation environment slipped compared with the previous year. According to the report, the weaker performance in the innovation environment reflected the need to improve the accessibility of venture capital for enterprise innovation and IP protection relative to the increased demand for both because of the growing recognition of the importance of IP in China. In 2015, the State Council formally recognized innovation and entrepreneurship as critical for achieving economic development. In addition China intends to relax rules applying to foreigners with technical talent seeking permanent residency or even citizenship in China, allow Chinese researchers to participate in projects outside of China, implement stronger IP protections, and increase market competition to boost innovation.[21] China's entrepreneurship base has a solid foundation in the 115 university science parks and 1,600 technology incubators/accelerators. Leveraging these infrastructure investments and resources are critical to China's advances in entrepreneurship. However, other issues such as the ability of companies in the market to truly compete independent of the influence of the State and partner with foreign companies in fair IP arrangements will have a great influence on their success.

4: China's Successes and Challenges in Nanotechnology R&D

China has made considerable investments in nanotechnology R&D since 2000. Substantial successes were achieved during this period in the number of patents issued to Chinese inventors, the number of publications and related citations and the creation of dedicated nanotechnology science parks.[28] These successes help to build a foundation for innovation. However, China has had difficulties in translating innovation into commercialization. In the sections that follow, China's successes and challenges in nanotechnology R&D are discussed.

Successes:

Patents issued

An important metric of innovation identified in the MLP was the number of Chinese patents issued to Chinese nationals annually. In 2008, 64% percent of nanotechnology patent applications to the US Patent and Trademark Office (PTO) were from American inventors.[26] However, Chinese innovators have been prolific in applying for and receiving domestic patents (i.e., in China). While overall applications to the State Intellectual Property Office (SIPO) of China were slightly less than applications to the US PTO in 2008 (18,438 versus 19,665), Chinese inventors represented ~89% of the applicants. US inventors ranked second with 4.4% of the total applicants to SIPO. In fact, in 2012 Chinese domestic resident patents accounted for 22.3% of the total number of patents submitted worldwide, which was second only to Japan.[21] The trend is similar even when the scope of the search is narrowed to micro- and nanotechnology patents. From 2011 to 2015, China ranked first in patent grants with 23.3% of the total patents granted worldwide.[29] Only 4% of 3460 patents were granted from patent offices outside China, whereas more than 57% of US patents were granted abroad (**Figure 4**). Most nanotechnology patent applications in the US are from the industrial sector whereas in China the clear majority is from academia.[26] The focus of China's patents strategy is clearly domestically focused with only ~5% filed with patent offices outside of China.[21] This is low when compared to the US where over 50% of domestic patent applications are filed internationally. The large number of patent applications as well as issued patents in China raises questions about patent strategy and breadth of coverage. As a result, it has been suggested that many of those patents are not used (i.e., licensed), which potentially limits their value and impact on China's economy.[25]

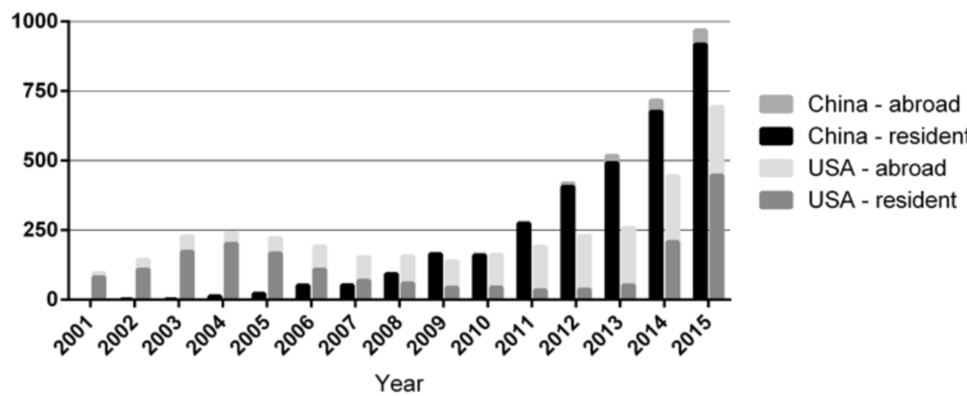

Figure 4. Resident and abroad counts of patent grants in micro- and nanotechnology in China and the United States, 2001-15 (Source: reference 29)

International citations of scientific papers

Between 2004 and 2014, China ranked second in the world in total number of science and technology publications and fourth in the rate of citations.[21] In addition, from 2001 to 2011 the increase in publication rate was steady at ~15% annually. While the increase in total publications has been impressive, gains in the citation rate for S&T papers have also been impressive. From 2004 to 2013 China produced 5.2% of the world's highly cited papers ranking fourth according to the Chinese National Innovation Index (2013).[21] The Chinese NII defines "highly cited" as papers that are in the top 1% of their fields with respect to citations. The US ranked first with nearly 40% of the highly-cited papers.[21] The NSF reported that the fraction of highly cited papers by China, as of 2012, was 37% lower than expected given their productivity.[21] In terms of nanotechnology papers, similar trends were observed. The annual publication totals during the period of 2001 to 2014 were collected using the Thomson Science Citation Index's (SCI) Web of Science database using the search term "nano* NOT nanomolar" to show the recent publication patterns of the two countries.[26] Both China and the US demonstrated steady growth in nanotechnology publications over the 14-year period that was analyzed. While China lagged behind the US from 2001 to 2009, it surpassed the US in 2011. In terms of bionanotechnology papers relating to cancer, China surpassed the US in 2013. However, as we noted in our analysis "there is a severe mismatch between China's high publication productivity and low citation numbers."[26,30] Like the analysis of patent trends, the recent higher Chinese publication rate (i.e., quantity) did not correlate linearly with citation rate (i.e., a measure of quality). It is also interesting to note that while China generally is much weaker than the US in nano-bio, in cancer bionanotechnology (a relatively small field) the countries are closer to parity depending on the metric used for evaluation. This is likely the result of cooperativity agreements between China and US. The application of nanotechnology to cancer research has proven to be an interesting case study and promising area for China–USA collaboration.[31] Joint support for cancer nanotechnology research by the NIH and NSFC started in 2010 and continues today. There is a solid trend of co-authorship between US and China authors in this area demonstrating the complementary interests and opportunities for cooperation in otherwise competitive research areas. The US–China Symposium on Nanobiology and Nanomedicine has been held every two years since 2008 and provides a unique opportunity for experienced scientists to exchange ideas and establish new collaborations. It helps to increase US–China cancer bionanotechnology partnerships including promoting new programs for reciprocal training and exchange, co-sponsoring workshops focused on specific cancer bionanotechnology topics of high priority to both countries, and joint financial assistance of collaborative research projects by Chinese and US funders.

Creation of dedicated nanotechnology science parks: Ecosystems for Nanotech Development
The government has played a central role in the development of nanotechnology in China. They've created policies, provided funding for R&D, infrastructure development and capacity building and importantly, they are a key source of venture funding.[28] Local (i.e., city) governments also have a history of supporting the field by building and supporting nanotechnology development centers in China. Included in these cities are Shanghai (Shanghai Nanotechnology Promotion Center), Tianjin (Nanotechnology Industrial Base of China), and Suzhou (China International Nanotech Innovation Cluster or CHINANO). Suzhou stands out among these centers because of its outstanding track record in manufacturing, its strong support of innovation and the funding invested. For example, Suzhou Innovation Park (SIP) launched the Nanopolis Suzhou initiative and committed $1.6 billion (USD) over a five-year period. The goals of Nanopolis are to

not only develop companies but also to provide a nanotech ecosystem. Nanopolis provides technology incubation, R&D, and pilot production. The initiative is focused on nanotech commercialization with an emphasis on micro- and nano-manufacturing technologies, energy and green technologies and nanomedicine. The investment in nanomedicine is particularly noteworthy given the significant strength of the US in nanobio and the need not only for development but, importantly, research in this area. A combination of incentives and support is provided by the Suzhou government and SIP including housing and manpower subsidies and tax reductions. Nanopolis Suzhou has IP development and protection services as well. Over an approximate 20-year period, Suzhou has had over 20,000 national and multinational company sponsors, has over 170 startups and more than 150 investment companies in SIP. For nanotechnology specifically, there are more than 20 investment companies focusing on nanotech incubation. In addition to Nanopolis, SIP initiated the State University Science Park for Nanotech, which is focused on developing research institutes and joint education programs for tech transfer and commercialization. Finally, bioBay was established by SIP in 2007 to develop the emerging biological industry focusing on bio and bionanotechnology. bioBay offers numerous services including IP services free-of-charge to the companies that they incubate. These services include residential housing, business rental and manpower subsidies, access to the nanotech characterization and fabrication facilities and they are eligible for start-up funding. Funding for bioBay is provided by the city government (Suzhou), the provincial government (Jiangsu), the State (MOST) and a variety of venture funds. The Chinese Academy of Sciences selected bioBay as the site for its Suzhou Institute of Nano-Tech and Nano-Bionics (SINANO). SINANO is a joint venture between the CAS, Jiangsu, Suzhou and SIP. Entrepreneurs selected for the program receive as much as $1.5 million USD but half of it is public investment. The downside to this funding model is that the company loses its financial independence.

Challenges:

Cao et al[28] eloquently described the formidable barriers that exist in China between the R&D ecosystem and private industry that result in a translation/commercialization pathway that does not function well. These barriers include: "(1) An environment that lacks rigid intellectual property right (IPR) protection making technology transfer difficult, if not impossible; (2) an immature venture capital market that discourages risk taking; and (3) the dearth of skillful and knowledgeable managers who understand not only technology but also financial, legal and other aspects of the technology transfer process."[28] There are also nanotechnology specific commercialization issues as well including special considerations regarding the environment and safety and the enormous investment required and time horizon for successfully introducing a nanotechnology-based product to the market. The coordination between scientists and engineers (both on the academic and industrial sides of the equation) and entrepreneurs is of critical importance to successfully transferring technology in a way that promotes commercialization. Finally, the entire "nano" field has been the subject of considerable hype – not just in China but worldwide. This combined with the fact that transformative results are scarce has cast a shadow on investment flow from the private sector. Furthermore, government funding agencies struggle with awarding long-term grants and have instituted a proof-of-concept requirement in the early stages of a project. Given the very long-term commercial prospects and investment heavy requirements of nanotechnology development, it is unrealistic to push for absolute early stage proof-of-concept using a commercialization standard rather than a scientific standard.

Research specialization areas in nanotechnology

In a recent analysis on research diversification and its impact in nanotechnology, Herron at al[32] demonstrated that Chinese nanoscientists were predominantly focused (i.e., specialized) in the areas of thin films and nanoparticles/self-assembly. In the US and EU, the areas of specialization are bio (i.e., nanomedicine and nanobiotechnology) and electronics (i.e., nanoelectronics and nanoptoelectronics). The publishing trends are shown in **Figure 5**. The Revealed Literature Advantage (RLA) for the US in bio is extremely high, which shows a very significant focus in nanomedicine and nanobiotechnology. The authors concluded that while the US is opening up new frontiers in nanobio and electronics other countries such as China are following but with a considerable lag. They go on to state "we interpret this as a reflection of a process of scientific catch-up, with the Newcomers [such as China] attempting to diversify by making up ground in areas such as nanobio, and the US and EU attempting to maintain a competitive edge in nanobio and electronics—two areas in which their industries have been investing heavily".

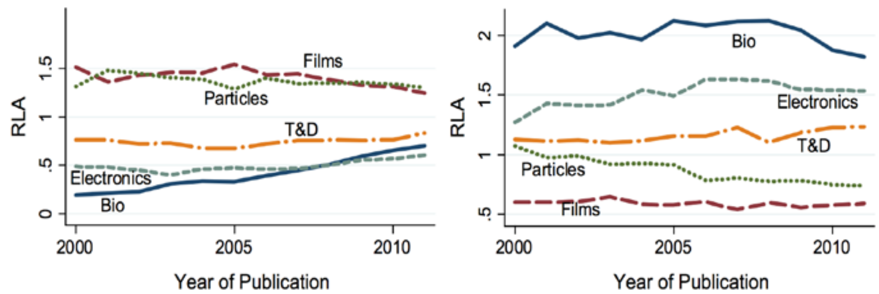

Figure 5. A plot of the Revealed Literature Advantage (RLA) versus year for China (left) and the US (right). The RLA is basically a ratio of a country's publications in a nanotechnology subfield to its total publications in nanotechnology. When the RLA is greater than 1, a country is considered to specialize in a subfield. From the data it can be seen that China is specializing in films and nanoparticles while the US is specializing in bio (nanomedicine and nanobiotechnology), electronics (nanoelectronics and nanoptoelectronics) and T&D (carbon nanotubes and quantum dots). (Reproduced from reference 32)

Intellectual Property Rights

China has been moving towards international standards and modern regulatory practices since about 2012. The commitment to IP protection may be pragmatic and a reflection of their ramped-up investment in S&T R&D. In other words, China wants to ensure that they protect their investment and the technologies that are created. Historically, China has not been IP friendly and there were serious problems with enforcement. Currently, there are more than 80 agencies involved with IP protection in China. Furthermore, three dedicated IP courts have been established in Beijing, Guangzhou and Shanghai.[21] However, it is fair to say that a fair degree of skepticism exists and only time will tell if IP enforcement is truly occurring and is effective. In the meantime, export control in the US especially as it relates to Universities and Research Institutes must continue to be vigilant in controlling the flow of materials, data and information to China.

Technology Transfer

Technology transfer is a widely recognized challenge in China. Promoting innovation and facilitating the translation of R&D projects into commercial products was a primary driver for China's heavy investment in science and technology parks and programs such as the Innovation Fund for Small Technology-based Firms (Innofund). Innofund provides funds to companies on a project-by-project basis in the form of grants, loans and subsidies. Despite the nearly $4.5 billion USD that was invested from 1999 to 2013 in all types of S&T projects by InnoFund, technology transfer and commercialization in China is lacking.[21] Currently, "imperfect university – industry links" are considered to be the major obstacle to technology transfer and commercialization in China since universities and research institutes are responsible for the vast majority of granted nanotechnology patents.[26] "The lack of interest in acquiring frontier knowledge in many industries and the lack of communication channels between academic institutions and industry hinder[s] the commercialization of nanotechnology-derived products [in China]".[26] As such, improving technology transfer and nanotechnology commercialization remains a priority for China. It is clear that the path forward needs to include continued improvements in intellectual property rights, the removal of barriers between academics and companies and the fostering of a venture funding market that is not risk averse and attracts investors from outside of the government and includes significant foreign investment.

5. Summary of Key Points and Recommendations for Congressional Action

A. **Nanotechnology in China** - China has had tangible successeses in publishing, domestic patenting and the creation of ecosystems in the form of science and technology parks, which incubate/accelerate R&D. However, China still struggles with an immature venture funding market, intellectual property protection, technology transfer and commercialization. The vast majority of Chinese nanotechnology patents are produced by universities and research institutes rather than companies. Poorly developed mechanisms of technology transfer along with weak university-industry networks lead to an insufficient product pipeline and a lack of commercialization. The lack of firm intellectual property protection also negatively influences technology transfer and venture investment.

B. **The Duality of Nanotechnology R&D** – Nanotechnology is a unique discipline that, unlike others, requires strong commitment to parallel funding of both basic research and commercial development. The commercialization of nanotechnology requires an enormous investment of funding and time due to factors such as the complexity of design, unexpected behavior, scalability and environmental, health and safety concerns. An industry focused on tight development timelines and a short horizon for an acceptable return-on-investment is not likely to have the patience for commercial nanotechnology product development especially in the bio space. In addition, there is a critical need to maintain and even increase basic research activities in nano science and technology in order to foster further discovery and inventions that will eventually become development candidates and fill a commercial pipeline.

C. **Financial Support of Nanotechnology R&D in the United States –** The U.S. can maintain its strategic advantage in nanotechnology by maintaining and possibly increasing its investment in research, development and commercialization. The NNI is the world leader in organizing, setting priorities and providing funding for nanotechnology R&D activities. However, after peaking in 2010, FY2018 federal support for nanotechnology R&D is projected to be at its lowest level since 2004 while China continues to increase investment. Since U.S. Gross Domestic Spending on R&D, including on nanotechnology, has been relatively constant since 2010, companies investment in R&D may be offsetting reductions in government support although it is likely that commercial development is emphasized over basic research especially in the bio-nano field. It is clear that overall U.S. dominance of the nanotechnology field since 2001 can be attributed to a firm government commitment to the NNI and substantial funding appropriations for R&D.

D. **Implications for the United States** – Reductions in nanotechnology R&D funding will have serious implications on the global competitiveness of U.S. business sectors such as information technology, healthcare and national security and defense. Nanotechnology is considered a dual use technology –one that can be reasonably anticipated to provide knowledge, products, or technologies that could be directly misapplied by others to pose a threat to public health, agriculture, plants, animals, the environment, or materiel. Therefore, reductions in nano funding would not only lead to reduced global competitiveness in healthcare and science and technology but also it could have serious implications on national defense as more than 60 countries have national nanotechnology development programs with their eye on dual use technologies.

E. Recommendations –

a. At least restore the appropriation to the NNI in order to maintain the position of the United States as the global leader in nanotechnology R&D.
   i. Appropriate funding for basic nanotechnology research programs. These programs require federal support since they are too "early stage" for industry.
   ii. Increase the fractional allocation of the Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs to further promote early-stage technology commercialization and partnerships between academia and industry.

b. Establish federally funded programs to support University intellectual property development and technology transfer programs. With the exception of a relatively few major U.S. universities, the vast majority of universities do not have an adequate commitment to developing and protecting IP. In addition, the quality of most university-based technology transfer programs is lacking.

c. Monitor Chinese intellectual property activities and progress on IP enforcement, actively engage the SIPO and encourage compliance with WTO standards.

d. Support the development of public-private partnerships to promote/expand the establishment of nanotechnology accelerator hubs. Developing nanotechnology ecosystems with a critical mass of resources in a single location will not only spur R&D but will also ensure the retention of high paying jobs in these centers in the United States.

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