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FOR COUNTERING WEAPONS OF MASS DESTRUCTION

Nanotechnology in a Globalized World:

Strategic Assessments of an Emerging Technology

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The Naval Postgraduate School Center on Contemporary Conflict is the research wing of the Department of National Security Affairs (NSA) and specializes in the study of international relations, security policy, and regional studies. One of the CCC's programs is the Project on Advanced Systems and Concepts for Countering WMD (PASCC). PASCC operates as a program planning and implementation office, research center, and intellectual clearinghouse for the execution of analysis and future-oriented studies and dialogues for the Defense Threat Reduction Agency.

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EXECUTIVE SUMMARY

Nanotechnologies are enabling, dual-use technologies with the potential to alter the modern world significantly, from fields as wide-ranging as warfare to industrial design to medicine to social and human engineering. Seizing the technological lead in nanotech is often viewed as an imperative for both 21st century defense and global competitiveness. Only revolutionary technologies are believed to allow a country to take advantage of its relative backwardness—in the sense of its lack of commitment to existing, incremental technologies—and leap ahead of existing technological leaders in developing and deploying a revolutionary new technology. New technologies, however, are only likely truly to revolutionize an economy and society if there is a broader national base that allows a new technology to spread and transform from its initial niche application, whether civilian or military, and if society is willing to adopt the technology in question. Globally, there is significant belief in the revolutionary potential of nanotechnology, not only to transform warfare, economy and society, but also the international geopolitical hierarchy. Between 2001 and 2014, over sixty countries followed the United States and established nanotechnology initiatives. These countries range from advanced industrial countries in Europe to Japan to the emerging markets of Russia, China, Brazil, and India to developing countries such as Nepal and Pakistan.

In order to understand the risks associated with nanotechnology with respect to U.S. national security and leadership and means for managing them, the report begins with an examination of some of nanotech's military applications, and interdisciplinary nature of nanotechnology. Definitional and data challenges make risk assessments of nanotech's security, market, safety, health and environmental impacts difficult. This difficulty is reflected in the lack of multilateral and national efforts to govern nanotechnologies for security purposes. The report then sketches the global landscape of national nanotechnology efforts, with brief looks at Brazil, India and Russia, the European Union, Germany, and the United Kingdom and a portrait of China. In order to understand nanotechnology's potential for technological surprise and disruption of the geopolitical position of the United States, it examines these empirical results against the background of the factors shaping government control of technological superiority. The report then concludes with an initial assessment of whether nanotechnology is revolutionary, and presents its key findings and policy recommendations. The findings presented here should be considered as preliminary, in that the report highlights central definitional and data challenges. Such conditions are ripe for overselling or underestimating nanotechnology's potential and prevent the provision of more definitive answers.

KEY FINDINGS AND RECOMMENDATIONS

- ❖ Nanotechnology is a general-purpose technology that is contributing to the ongoing revolution in information and communications technologies, microelectronics and robotics.
- ❖ Nanotechnology is unlikely to provide the basis for novel weapons of mass destruction or mass effect. Such applications, though notional, would be most likely in the chemical and biological spheres.
- ❖ Nanotechnology, if widely adopted, is likely to dramatically improve the health and resilience of armed forces personnel and the public and potentially even reduce resource scarcity as a cause of war. Widespread adoption is uncertain, however, as considerable concern exists over environmental, health, and safety risks.
- ❖ Governance specific to dual-use and military applications of nanotechnology at the multilateral or national levels is generally absent. In its stead, there is increasing devolution of responsibility for national security to corporations and individual scientists.[1] U.S. agencies should work internationally to generate new multilateral norms and rules governing nanotech development and use, as well as with academics and corporations to foster a culture of nano-security and dual-use awareness and codes of conduct for research and development.
- ❖ Awareness of nanotechnology advances is hindered by the questionable comparability and quality of existing indicators on nanotechnology research and development. Rigorous data collection is needed on nanotechnology's military and commercial applications and health, safety, and environmental impacts and to support interdisciplinary collaboration between scientists, policymakers, defense practitioners, and market actors to facilitate comparative longitudinal, cross-national and global supply-chain data collection and measurement.
- ❖ Based on available data, the United States remains the leader in nanotechnology. Other Asian countries, including China, are expanding and improving their nanotechnological base. In order to maintain its position, the USG should continue its investment in nanotechnology, with an ongoing and sustained commitment to basic R&D and increased assistance in the commercialization of nanotech applications.

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[1] Margaret E. Kosal, "Strategy, Technology, and Governance: Shift of Responsibility from Nation-states to Individuals," Presentation prepared for delivery at the Society for the Study of Nanoscience and Emerging Technologies 5th Annual Meeting, Boston, MA, October 27-29, 2013

I. Introduction: The Global Pursuit of Nanotechnology

Often hailed as the next "technological revolution," nanotechnology is being pursued by countries aspiring to enhanced wealth and influence in world politics. Nanotechnologies are enabling technologies with the potential to significantly alter the modern world, from fields as far flung as warfare to industrial design to medicine to social and human engineering. Nanotech is not merely about size, it is about the unique physical, chemical, biological and optical properties that emerge naturally at the nanoscale and the ability to manipulate and engineer such effects. It is a broad new area of science, involving physics, chemistry, biology, materials science, and engineering at the nanoscale.

Seizing the technological lead in nanotech is often viewed as an imperative for global economic competitiveness and 21st century defense. Technological change offers both hope and concern over national prosperity and security. It raises the prospects of tremendous increases in wealth, productivity, and quality and length of life. Technological change, however, can disrupt entire national and global industries and dramatically shift the relative wealth of nations—if the technology in question is truly revolutionary. Technological change can restructure warfare and defense, empower non-state actors as well as states, and wreak destruction on human life and the environment.

Nanotechnology has captured the imagination of national governments as the foundation for a technological revolution. Nanotechnology's potential for disruption led former Deputy Under Secretary of Defense Clifford Lau to herald it as leading to a new revolution in military affairs, one more important than the invention of gunpowder.[2] A former U.S. official stated that nanotechnologies "have even greater potential than nuclear weapons to radically change the balance of power" and will alter warfare more than the invention of gunpowder.[3] Russian President Vladimir Putin stressed that Russia needs an "innovation army" using nanotechnology to keep up in a new

[2] Barnaby J. Feder, "Frontier of Military Technology is in the Size of a Molecule," *New York Times*, April 10, 2003

[3] David Jeremiah, "Nanotechnology and Global Security." (Palo Alto, CA; Fourth Foresight Conference on Molecular Nanotechnology), November 9, 1995; Clifford Lau, Deputy Undersecretary of Defense for Basic Research, cited in (Feder 2003)

high tech arms race.[4] Some of the most worrisome aspects of nanotechnology are the potentials for new biological, chemical, or nanomaterial weapons and delivery mechanisms.[5]

Governments have incorporated nanotechnologies and emerging technologies as part of their "smart goals" for competitiveness and are investing considerable funds in them. U.S. politicians have argued that, "U.S. economic competitiveness in the global marketplace depends on success in developing a vibrant and innovative nanotechnology community."[6] In 2005, the United Nations Task Force on the Millennium Development Goals touted nanotech as one of three platform technologies that can reduce hunger, promote health, improve water sanitation, develop renewable resources and improve the environment, and recommended that developing countries create nanotech programs.[7] Inspired by such forecasts, between 2001 and 2014, over sixty countries followed the United States and established nanotechnology initiatives. These countries range from advanced industrial countries in Europe and Japan to the emerging markets of Russia, China, Brazil, and India. More recently, Malaysia and Singapore have established national nanotechnology initiative, and some of the latest ones have appeared in Nepal, Sri Lanka and Pakistan.[8]

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[4] Vladimir Putin, quoted in "Putin Warns of New Worldwide Arms Race," www.chinaview.cn February 8, 2008.

[5] Margaret E. Kosal, *Nanotechnology for chemical and biological defense.* (New York: Springer, 2009).

[6] George Allen, "The Economic Promise of Nanotechnology," *Issues in Science & Technology* (Summer 2005). Online: http://issues.org/21-4/allen/.

[7] Juma, Calestous, Lee Yee-Cheong, Technology and Innovation Un Millennium Project. Task Force on Science, and Programme United Nations Development, *Innovation : applying knowledge in development*, Edited by Calestous Juma, Lee Yee-Cheong, Technology and Innovation Un Millennium Project, Task Force on Science and Programme United Nations Development, *Applying knowledge in development*. London ; Sterling, Va.: London ; Sterling, Va.: Earthscan (2005); Salamanca-Buentello, Fabio, Deepa L. Persad, Erin B. Court, Douglas K. Martin, Abdallah S. Daar, and Peter A. Singer, "Nanotechnology and the Developing World (Policy Forum)." *PLoS Medicine* 2 (5), 2005; P. Singer., F. Salamanca-Buentello, and A. Daar, "Harnessing Nanotechnology to improve global equity: the less industrialized countries are eager to play an early role in developing this technology; the global community should help them." *Issues in Science and Technology* 21 (4), 2005.

[8] Mihail Roco, *Nanotechnology research directions for societal needs in 2020 retrospective and outlook*. Edited by Chad A. Mirkin, Mark C. Hersam and SpringerLink (United States] : Dordrecht ; New York: United States : World Technology Evaluation Center ; Dordrecht ; New York : Springer, 2011a); Donald Maclurcan, "Nanotechnology and Developing Countries - Part 2: What Realities?" *AzONano-Online Journal of Nanotechnology* 1 (2005); ETC Group, "Geopiracy: The Case Against Geoengineering" (2010); X. Li et al., "Worldwide Nanotechnology Development: A Comparative Study of USPTO, EPO, and JPO Patents (1976–2004)." *Journal of Nanoparticle Research* 9:977–1002 (2007)

Billions of dollars have been put towards nanotech.[9] In 2011, Lux Research estimated that total global funding for nanotechnology (public and private) in 2010 was $17.8 billion dollars, of which corporate R&D funding was $9.6 billion. Governments invested about $10 billion in nanotech in 2011, with an expected growth rate of 20% in annual government funding over 2012-15.[10] The U.S. government alone has provided almost $20 billion in nanotechnology funding over the 2001-14 period.[11] Chinese government support for nanotechnology is estimated to have grown at a rate of 30-45% a year since 2004.[12] Through 2010, global government expenditures in nanotechnology were estimated to have reached $67.5 billion.[13] Cumulative corporate and private funding through 2015 for nanotech R&D is estimated to amount to an additional $150 billion.[14]

In this age of globalization, almost all advanced technology may be deemed dual-use, as countries pursue both spin-on (military) and spin-off (civilian) strategies of technological innovation. Governments face tradeoffs between security and the need for government control, and economic competitiveness and the openness necessary for innovation. Whether national military and economic advantage can be manufactured and maintained in a world of global corporate (R&D) and production alliances is, however, a subject of debate. If nations can create and maintain the technological lead in revolutionary emerging technologies, the assumption is that their military and economic competitiveness will overtake and supplant contemporary military and industrial leaders, including the United States.

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[9] John F. Sargent, Jr., Nanotechnology: a policy primer. (Congressional Research Service Report, 2013).

[10] John F. Sargent, Jr., "Nanotechnology: a policy primer. (Congressional Research Service Report 2010); Cientifica, "Half Way to the Trillion Dollar Market? A Critical Review of the Diffusion of Nanotechnologies, Market Report. Research Policy" (2013);Cientifica, "Global Funding of Nanotechnologies and Its Impact" (2011).

[11] NNI, "Frequently Asked Questions." U.S. National Nanotechnology Initiative (NNI), 2014.

[12] Anne L. Clunan, personal communication with senior member of the U.S. Office of Science and Technology Policy (OSTP) Nanoscale Science, Engineering, and Technology (NSET) Subcommittee and the National Nanotechnology Coordination Office (NNCO), Washington, DC, May 30, 2013.

[13] John F. Sargent, Jr., "Nanotechnology: a policy primer.(Congressional Research Service Report 2010); Cientifica, "Global Funding of Nanotechnologies and Its Impact" (2011).

[14] Cientifica, "Global Funding of Nanotechnologies and Its Impact" (2011).

THIS REPORT

There is at present great uncertainty about whether nanotech is truly revolutionary or will merely produce incremental improvements in military and civilian applications. There is a need to take stock of current national efforts in the nanotechnology field and the literatures on technological revolutions and technological innovation to provide a framework for a preliminary assessment of nanotech's revolutionary potential, risks, and management. This report provides the results of such an exercise to investigate nanotechnology's potential to disrupt economic paradigms and revolutionize countries' economic and political-military positions internationally. The report represents the first year of work in a broader multi-year research effort. That broader effort will undertake a comprehensive cross-national analysis of: the threats to and opportunities for U.S. national security and economic prosperity from commercial and military nanotechnology; divergent national nanotechnology developmental strategies; and nanotechnology governance structures emerging in and across critical countries. This report takes stock of current national efforts in the nanotechnology field and the literatures on technological revolutions and technological innovation to assess nanotechnology's potential to disrupt military and economic paradigms and revolutionize countries' economic and political-military positions internationally. It assesses the challenges and opportunities in the risk assessment and management of emerging and dual-use nanotechnologies and the potential for technological surprise arising from their application. The report is organized around four central questions:

What is nanotechnology?

What is the state of nanotechnology governance?

What is the global nanotechnology research and development (R&D) landscape?

Will a nanotechnology revolution surprise us?

The findings presented here should be considered as only preliminary in that the report highlights central questions related to evaluating nanotech, without providing any definitive answers, as these require further research. In part, this tentativeness reflects the uncertainty surrounding investigations into any emerging technology; more specifically, it stems from the current lack of a consensual basis for defining and measuring what nanotechnology is and, therefore, the significant difficulty in evaluating existing data that are often non-comparable and of questionable quality. Such conditions

are ripe for overselling or underestimating nanotechnology's potential; the report attempts a clear-eyed assessment based on publicly available data and the evaluations of scholars and policy practitioners.

The challenges and requirements of assessing nanotechnologies is the subject of section II. The question, "what is nanotechnology?" does not have a simple answer. Here the focus is on the military applications of nanotech, and definitional and measurement problems that make it difficult to establish regulatory definitions and standards governing nano-enabled technologies. Section III, on governance, surveys the multilateral, national, and commercial regimes for dual-use technology, and finds that there is little effort to create new, nanotech-specific technology controls or multilateral governance mechanisms. Section IV provides a global overview of national efforts in nanotechnology and the rapid diffusion of national nanotechnology initiatives, with a quick look at Brazil, India, and Russia, snapshots of the European, German, and British approaches, and an in-depth portrait of China's approach to regulating strategic economic sectors and efforts in nanotechnology development. Section V turns to the contemporary conditions shaping national efforts to move to the forefront of technological innovation. It considers whether nanotechnology is likely to allow technological laggards to displace the United States economically and politically. The final section examines the expected consequences of disruptive and revolutionary technologies to address the question of technological surprise. It provides a preliminary assessment of whether the hype and hope about nanotechnologies' revolutionary potential is warranted. The report concludes with policy recommendations and suggestions for areas for further research.

II. What Is Nanotechnology

According to the U.S. National Nanotechnology Initiative, "nanotechnology is the understanding and control of matter at the nano-scale, at dimensions between approximately 1 and 100 nanometers, where unique phenomena enable novel applications. Encompassing nanoscale science, engineering, and technology, nanotechnology involves imaging, measuring, modeling, and manipulating matter at this length scale."[15] One nanometer is a billionth of a meter, or 10^{-9} of a meter (for a sense of scale, the size ratio between a nanometer and a meter is roughly that of a marble to the planet Earth). Physicist Richard Feynman, in a famous 1959 speech that foretold the

[15] "What it is and how it works," National Nanotechnology Initiative, May 20, 2012.

development of nanoscience, spoke of "plenty of room at the bottom."[16] It was not, however, until the late 1980s that scientists developed some of the tools and materials necessary to explore the manipulation of matter at the atomic and nano scale.

Nanotech is not merely about size, it is about the unique physical, chemical, biological and optical properties that emerge naturally at the nanoscale and the ability to manipulate and engineer such effects. It is a broad new area of science, involving physics, chemistry, biology, cognitive science, materials science, and engineering at the nanoscale. "Notable recent developments include organically growing nanoenabled solar cells in the form of wallpaper or as paint; silicon nanoparticles covered with a layer of gold and used in combination with infrared light to destroy cancerous tumors; silicon coated nanowires that form a highly efficient paper-like "sponge" to separate oil from water after, for instance, an oil spill; and nano-products that help to purify, desalinate and disinfect water, or store energy more efficiently."[17]

A central hurdle in attempting to evaluate nanotech's potential impact on national security and competitiveness is that there is neither a consensual definition of what constitutes nanotechnology or even the nanoscale, nor, as a result, comparable and reliable data and metrics for measuring it. This section first discusses some of the dual-use applications of nanotechnology and the governance challenges they pose, and then reviews the definitional and measurement issues hindering accurate assessments of nanotechnology.

AN ENABLING, DUAL-USE TECHNOLOGY

Nanotechnology may represent the ultimate dual-use enabling technology, as it is devoted to nanoscale device construction and manipulation across any number of biological, chemical and physical platforms. Currently, there are over 1,600 commercial products relying on nanotech. Nanotech is today used in synthetic biology, defense applications, electronics, medicine, agriculture and food production, industrial and textile manufacturing, cosmetics, mountain bikes, cars and other consumer products, and environmental remediation.[18] Nanotechnology, like biotechnology, faces a

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[16] R.P. Feynman, "There's plenty of room at the bottom (data storage)." *Journal of Microelectromechanical Systems* 1 (1):60–66, 1992.
[17] Robert Falkner and Nico Jaspers, "Regulating Nanotechnologies: Risk, Uncertainty and the Global Governance Gap." *Global Environmental Politics* (2012), p. 35.
[18] The Project on Emerging Nanotechnologies, "Inventories," (2012).

"dual-use dilemma," in that the facilities, material, and knowledge used for peaceful purposes in research and development for chemicals, medicines, sensors, textiles, and other materials can be used for military and weapons purposes.[19]

There is considerable ongoing research and development into military applications of nanotechnology. Some of these applications include:

> *Nano-electronics.* Nanotechnology combines with information and communications technology (ICT) to yields smaller, lighter, faster, and much more energy-efficient and easily deployable devices that enable real-time situational and information dominance that integrates the battlefield and strategic command. Nano-electronics are substantially enhancing everything from information operations (IO), data processing and flow, precision guidance of munitions, manned and unmanned vehicles, to individual human cognition and motor control.[20]
>
> *Nano-coatings.* Applications of nano-coatings are used to stabilize highly explosive materials, making it much safer to handle nuclear and other warheads. Nano-coatings can also stabilize biological and chemical agents, making them longer lasting and diversifying their means of delivery. Radio-frequency shield coatings could provide privacy and security to shield buildings and wireless networks from radio waves.[21]
>
> *Nano-optics.* Nano-engineered negative index metamaterials are moving stealth technology toward cloaking and invisibility, based on their ability to deflect light away from around an object rather than reflect it. Optical fibers married with nanowires portend the advent of solar-rechargeable, portable and wearable electronic devices.[22]

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[19] Ronald M. Atlas and Malcolm Dando, "The dual-use dilemma for the life sciences: perspectives, conundrums, and global solutions," *Biosecurity and bioterrorism : biodefense strategy, practice, and science* 4 (3):276, 2006.

[20] Margaret E. Kosal, "Nanotechnology Threat Anticipation," unpublished presentation, September 3, 2012.

[21] S. S. Azim, et al, "Studies on Graphite Based Conductive Paint Coatings," *Progress in Organic Coatings* 55(1): 1-4, 2006.

[22] B. Weintraub, Y. G. Wei, and Z. L. Wang, "Optical Fiber/Nanowire Hybrid Structures for Efficient Three-Dimensional Dye-Sensitized Solar Cells," *Angewandte Chemie*-International Edition 48(47): 8981-8985, 2009.

Nano-sensors and nano-monitors. Quantum dots allow for tagging any object and monitoring its location and use. U.S. researchers have developed a chemical weapons sensor chip that is powered by a smart phone; others are developing chemical weapons sensors based on the chemical-sensing capability of nanoparticles in the wings of Morpho butterflies. Similar detectors for improvised explosive devices are in development.[23] These tools will greatly enhance the detection of chemical, biological, radiological, nuclear and explosive (CNBRNE) materials. For example, "As part of a fielded sensor or diagnostic system, a nanoenabled bio-IO weapon could exploit indigenous agricultural or bacterial systems as a means for surveillance, making use of plant, insect, or animal sentinels as part of a larger sensor network. The sensor network may also include nanoenabled motes or advanced nanosatellites and leverage handheld personal devices such as cell phones, iPods, or PDAs."[24] These tools may also be reversed to serve as activators of such devices as well.

Nano-textiles. A tremendous amount of R&D is being devoted to develop nano-textiles that improve the performance and health of the individual soldier. Nanofabrics are being developed to enhance soldier armor and uniforms so as to reduce weight, provide ballistic protection, temperature modulation, trap germs, deliver real-time diagnosis and treatment of soldier health and detect exposure to electro-magnetic, radiological, biological and chemical weapons *in situ*. These textiles would be self-diagnosing and self-preparing. China, among others, has indigenously developed and deployed a nano-enabled space suit. The United States has invested $50 million in the Institute for Soldier Technologies at the Massachusetts Institute of Technology.

Nano-unmanned devices. Nanorobots, such as unmanned aerial vehicles, offset and allow for manpower reductions, and enhance surveillance and allow for control of nuclear weapons and CBRNE. The Defense Advanced Projects Agency (DARPA) has demonstrated a nano-

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[23] Angela Jones, Jeanne Nye and Andrew Greenberg, "Nanotechnology in the Military: National Defense, Homeland Security," Presentation prepared as part of the *Small Science, Big Decisions* project, University of Wisconsin, Madison Institute for Chemical Education, March 2011.
[24] Margaret E. Kosal, *Nanotechnology for chemical and biological defense*. (New York: Springer, 2009), pp. 95-96.

hummingbird capable of infiltrating buildings for indoor as well as outdoor surveillance.[25] The United Kingdom introduced a tiny nano-helicopter for reconnaissance patrol in Afghanistan. Microsatellites are made possible through nanotechnology.[26] Increased miniaturization will enable virtually invisible nano-motes to provide real-time monitoring.

Nano-weapons. Nanotechnology is being studied for its impact on energetics and in the life and medical sciences for new media for delivering therapeutic agents; the U.S. and Indian militaries are researching nanotech for defense against chemical and biological warfare. Nano-engineered explosives increase destructive force with a decrease in weight, allowing for lighter, more energetic payloads that may rival nuclear weapons for weight-to-energetic force ratios. The Russian government in 2007 exploded what it claimed was a nanotechnology-enabled thermobaric air-fuel bomb, although it is disputed whether this "father of all bombs" contained novel nanotechnologies or relied on well-known naturally occurring energetic properties of metals.[27]

The most likely offensive application of nanotechnology in the chemical and biological realm, according to a recent study, arises from combining nano-engineered structures and materials with biological agents to create novel nano-enabled biochemical weapons, potentially ones that are not affected by existing countermeasures. "Nanotechnology's primary role in transforming today's benign research advances into the future [biological] threats envisioned may be in providing structures at the molecular level that aid in the dissemination and stabilization of novel agents and the design of those agents to achieve the desired negative outcome…. A nanomaterial … may enhance the stability of a threat agent to facilitate weaponization, improve delivery efficacy, or modify the pathway of infection."[28]

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[25] DARPA, "Time Magazine Recognizes Darpa's Hummingbird Nano Air Vehicle," November 24 2011. http://www.darpa.mil/NewsEvents/Releases/2011/11/24.aspx

[26] Giulio Monzoni, "Micro and Nanotechnology Applications for Space Micropropulsion" in Nitaigour Premchand Mahalik, ed., *Micromanufacturing and Nanotechnology* (Dordrecht: Springer, 2006), pp. 197-218.

[27] BBC News, "Russia Tests Giant Fuel-Air Bomb," September 12, 2007.; F. Westerlund, *Russian Nanotechnology R&D: Thinking Big about Small Scale Scie*nce, (Stockholm: Swedish Defense Research Agency, 2011); p. 33.

[28] Margaret E. Kosal, *Nanotechnology for chemical and biological defense*. (New York: Springer, 2009), p. 90.

Additionally, nano-enabled weapons may be developed that allow for disruption of the immune system, effectively defeating countermeasures and potentially creating new agents.[29]

Another potential nano-weapon would be the deployment of toxic nanoparticles in means similar to biological or radiological weapons. Currently, the toxicity of nanoparticles is the subject of intense research and debate. Current production of common nanomaterials, such as nanosilver and carbon nanotubes, is still quite limited, in the range of hundreds to thousands of tons, while production of nano-titanium dioxide (widely used in cosmetics and paint) is in the millions of tons.[30] Large-scale commercial production of nanoparticles is expected to increase rapidly over the next fifteen years. Should results confirm the toxicity of such nanoparticles, future ease of access and low cost may make them attractive as "conventional" weapons of mass destruction or effect.[31]

The specter of automated molecular manufacturing based on self-replicating systems and artificial intelligence has led some to forecast a dismal future. Nanotechnology, in this view, will lead to a new global and extraordinarily expensive arms race for technological dominance, a dramatic increase in military instability, and reduced threshold for war. It will also augur the collapse of international trade, as nanotechnology allows the local production of goods once requiring foreign components.[32]

Defining Nanotechnology: No Consensus

A key challenge in efforts to assess nanotechnology's potential and current use is definitional. One of the most popular definitions of nanotechnology is that of small size—in that one nanometer is a billionth of a meter. Of the competing definitions of nanotechnology, many mainly focus on size. Most accept that the term "nanoscale" is defined as a size range from approximately 1 nm to 100

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[29] Margaret E. Kosal, *Nanotechnology for chemical and biological defense.* (New York: Springer, 2009), pp. 96-97.
[30] Tobias Sonderer, *Risk Assessment of Engineered Nanoparticles Based on Probabilistic Material Flow Analysis*, Master's Thesis (Zurich: Eidegenössische Technische Hochschule, 2009), p. 7.
[31] Margaret E. Kosal, *Nanotechnology for chemical and biological defense.* (New York: Springer, 2009), pp. 93-95.
[32] Jürgen Altmann and Mark Gubrud, "Anticipating military nanotechnology." *IEEE Technology and Society Magazine* 23 (4):33-40, 2004.

nm, though a scientifically based range goes from the atomic scale (0.2 nm) to 100 nm.[33] The focus on the 1-100 nm range relates both to the convenience of some standard definition that can be used to categorize nanotech, nanoscience and nanoproducts, as well as to the quantum mechanical and other effects (especially those related to surface area) that are observed at this scale. The closer a material is to the 1 nm end of the range, the more quantum, as opposed to classical, mechanical effects are observed, while closer to the 100 nm end, classical effects are more present.

In addition to the imprecision as to what nanotechnology is, it is also unclear how to define what it does, or even its effects. There currently does not exist any consensual statistical definition of nanotechnology, which makes assessment of military and commercial potential, actual market value, and risks to environment, health and safety difficult. The lack of definition also significantly complicates efforts to regulate the use and production of nanotechnology, as discussed below in the section on governance of nanotechnology. There continues to be considerable debate on what a statistical definition should be, bounded largely by two concerns: 1) the term should meaningfully connect a set of activities that have more in common than mere size, given the extraordinarily broad and diverse set of scientific and engineering disciplines operating at this scale; and 2) the definition should not be so limiting as to exclude future and emerging technologies that relate to the novel effects possible at the nanoscale.[34]

Why Definitions Matter

Size itself does not necessarily matter from a security, commercial, risk or regulatory point of view, as it is the nature and manipulation of nanoscale materials themselves that produce the novel properties and effects of interest.[35] A definition based purely on size does not distinguish between naturally occurring versus engineered nanoscale effects. For example, gold and silver particles at the nanoscale naturally exhibit fundamentally different properties than at the macroscale. At the macroscale, gold is an inert, nonmagnetic yellow metal. Gold at the nanoscale has quantum

[33] SCENIHR, "3.2. Definitions and Scope: The Appropriateness of Existing Methodologies to Assess the Potential Risks Associated with Engineered and Adventitious Products of Nanotechnologies," 2006.
[34] George Khushf, "The Ethics of Nanotechnology. Vision and Values for a New Generation of Science and Engineering," *Emerging Technologies and Ethical Issues in Engineering: Papers from a Workshop, October 14-15, 2003*, pp. 29-56, National Academy of Engineering, editor. The National Academies Press, 2004; pp. 33-36.
[35] Nanowerk, "Definition of the Term Nanotechnology," 2013.

properties that make it catalytic, insulating, and magnetic. At different sizes and after absorbing different wavelengths of light, gold nanoparticles can look red, purple, black or green, a property discovered at least as early as ancient Roman times.[36] Engineered gold nanoparticles are used in nanoelectromechanical systems, bioengineering, electronic textiles, nonlinear optics, among other applications.[37] Silver is a widely used metal in nanotech applications. Silver nanoparticles exhibit antimicrobial (antibacterial and antiviral) properties, and have engineered into nanofibres used in clothing and medical supplies, such as wound dressings.[38] Both gold and silver nanoparticles are useful in medical applications such as bioluminescence, biological sensors, labels, and therapeutics, and in electronics applications for insulating against and conducting electrical charges.[39] Similarly, carbon nanofibers have long been understood to be extremely strong and light, but very difficult to bond to other materials. When U.S. corporation Zyvex Technologies developed a means to suspend carbon nanotubes (CNT) in a resin (trademarked Kentara), they broke this developmental barrier; commercial applications of their technology include carbon-nanotube-enhanced mountain bikes, baseball bats, and automobiles.[40] Nanotechnology is widely used in semiconductor manufacturing, and owing to its surface area properties, has enabled much more massive computing power to come from billions of tinier and tinier transistors while reducing energy leakage. So while, size is a key aspect, nanotechnology is best thought of as an enabling technology, in that the *manipulation* of materials at the nanoscale is what produces new properties, whether in biology, chemistry, physics, electrical engineering, and any number of other disciplines.

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[36] Rosamund Daw, "Nanotechnology is Ancient History," *The Guardian*, April 24, 2012. http://www.theguardian.com/nanotechnology-world/nanotechnology-is-ancient-history

[37] Kenneth Chang, "Tiny is Beautiful: Translating 'Nano' into Potential." *The New York Times*, February 22, 2005; Siegel et al., "Properties of gold nanostructures sputtered on glass," *Nanoscale Research Letters* (2011); Janice L. Speshock et al., "Silver and Gold Nanoparticles Alter Cathepsin Activity In vitro," *Nanotscale Research Letters* 6 (17) (2011)

[38] Yasutaka Mori et al., "Antiviral activity of silver nanoparticle/chitosan composites against H1N1 influenza A virus," *Nanoscale Research Letters* 8 (93) (2013); Sirajo Umar et ally potent silver-organoalkoxysilane antimicrobial porous nanomembrane," *Nanoscale Research Letters* 8 (164) (2013); Janice L. Speshock et al., "Silver and Gold Nanoparticles Alter Cathepsin Activity In vitro," *Nanotscale Research Letters* 6 (17) (2011)

[39] Yu Tao, Yuxiao Tao, Biaobing Wang, Liuyang Wang, and Yanlong Tai, "A facile approach to a silver conductive ink with high performance for macroelectronics," *Nanoscale Research Letters* 8 (296), 2013.

[40] Margaret E. Kosal, "Nanotechnology Threat Anticipation," unpublished presentation, September 3, 2012; p. 16.

The European Union has targeted size as the decisive factor in defining a nanomaterial. According to the European Commission's Recommendation 2011/ 6962 on the Definition of Nanomaterial, a 'nanomaterial' covers natural, incidental, or manufactured material containing particles in an unbound state or as an aggregate or as an agglomerate, and where fifty percent or more of the particles in the number size distribution have one or more external dimensions in the range of 1 nm–100nm. This fifty percent criterion is waived when warranted by environmental, health, safety or competitiveness concerns. The EU definition also includes a surface area by volume measurement of $60m^2/cm^3$ as fitting the definition of nanomaterial. In addition, certain materials, such as fullerenes, graphene flakes and single wall carbon nanotubes with one or more external dimension below 1 nm, are considered nanomaterials.[41]

The International Organization for Standardization defines a nanomaterial as 'material with any external dimensions in the nanoscale or having internal structure or surface structure in the nanoscale' while the Scientific Committee on Emerging and Newly Identified Health Risks of the European Commission defines it as "material with one or more external dimensions, or an internal structure, which could exhibit novel characteristics compared to the same material without nanoscale features."[42] The ISO definition, like the EU one, is based purely on size, rather than the unique properties found at the nanoscale. In general, this approach provides much more comprehensive regulation of all nanomaterials.

The United States has taken a different approach that takes into account not only on size, but also on the new properties that arise from manipulating nanoscale materials. According to the U.S. National Nanotechnology Initiative (NNI), "nanotechnology is the understanding and control of matter at the nanoscale, at dimensions between approximately 1 and 100 nanometers, where unique phenomena enable novel applications. Encompassing nanoscale science, engineering, and technology, nanotechnology involves imaging, measuring, modeling, and manipulating matter at this length scale." The SCENIHR, basing their opinion on the United Kingdom's Royal Society and Royal Academy of Engineering definitions, also takes this approach, defining nanotechnology as

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[41] EU Recommendation 2011/696/EU of 18 October 2011 on the Definition of Nanomaterial.
[42] ISO, "Nanotechnologies Vocabulary Part 5: Nano/bio interface" (2011); SCENIHR, "3.2. Definitions and Scope: The Appropriateness of Existing Methodologies to Assess the Potential Risks Associated with Engineered and Adventitious Products of Nanotechnologies" (2006)

"the design, characterization, production and application of structures, devices and systems by controlling shape and size at the nanoscale."

Related to problems of definition, the second major problem is the availability, reliability, and validity of data on nanotechnology, as shown in the next section.

The Problem of Data

The public buildup of nanotechnology's promise has been spurred in part by widely varying reports and data about what it is, what it does, its military and commercial importance and its effects. Nanotechnology estimates vary widely according to data collectors (only a few companies and individuals), techniques for calculating market size, sources of funding (public and private), and effects (security, economic, health and environmental impacts of nanotechnology).

Nanotechnology has captured the imagination of defense and development officials because of what Margaret E. Kosal terms the "hype and horror" scenarios surrounding nanotech development in its early years.[43] On the "horror" side of the equation, popular fantastical stories of self-replicating nanobots run amok led to great concern among nongovernmental organizations and a few arms control advocates about the negative implications of this technology. On the "hype side" are claims that nanotech would erase scarcity and lead to a global economy of abundance. Such accounts promised that nanotech would clean the water and the air, eradicate hunger and poverty, cure cancer, remove many of the resource rationale for war and conflict, and end global capitalism through local production. The designation of nanotech as a key technology for economic development and technological competitiveness by entities ranging from the United States government to the United Nations and the World Bank have only added to the hope that nanotech will be revolutionary. These factors have created significant demand for data on nanotech: how much is being spent, by whom, in what areas, and with what expectation of military, market and societal value. The question then becomes: where does this data come from, and is it any good?

Many news sources cite the outpouring of government and private-sector spending on nanotechnology and the growing number of nanotechnology firms and products. There are, however, only a few entities that produce the data widely employed in government, media, scholarly,

[43] Personal communication with Margaret E. Kosal, San Francisco, April 2, 2013.

and business assessments, making it difficult to ascertain the data's quality and comparability as well as the actual outcomes the data claims to measure.

In the nanotechnology field, two private technology consulting firms, Lux Research and Cientifica, and one individual, Mihail Roco of the U.S. National Science Foundation, have created the most widely used metrics and data for measuring nanotech-competitiveness, nanotech products, and nations' positions in a global nano-hierarchy. These actors have been particularly powerful in shaping international and national investments in nanotechnology. Their influence in shaping public and commercial perspectives is problematic, given the lack of a precise definition of nanotechnology and in that these actors employ quite different methodologies.[44] Their data are used by virtually every national government in comparing their national position with others, even though senior U.S. government officials are aware that their data and methodology may be questionable.[45] The OECD, recognizing this issue, has recently entered into the compilation of nanotechnology metrics, and began publishing data on nanotechnology R&D in 2011.[46] The OECD, in turn, depends to a large degree on methodologies developed by three academics, Alan Porter, Philip Shapira and Jan Youtie, of the Georgia Institute of Technology in the United States.[47] These metrics include the following: market value of nanotechnology; government, higher education, and business expenditures on R&D;

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[44] ETC Group, "Geopiracy: The Case Against Geoengineering," (2012) gives a good break down of the different methodologies used by these firms. To further complicate matters, Lux Research stopped compiling nano-specific data in 2010. According to Roco, Lux Research does not include the electronics sector in its data, a sector where nanotechnology has been used for a number of years to increase performance. Anne Clunan, personal communication with Mihail Roco, Washington, DC, May 30, 2013.

[45] Anne Clunan, personal communication with Mihail Roco, Washington, DC, May 30, 2013; Anne Clunan, personal communication with five senior members of the U.S. Office of Science and Technology Policy (OSTP) Nanoscale Science, Engineering, and Technology (NSET) Subcommittee and the National Nanotechnology Coordination Office (NNCO), Washington, DC, May 31, 2013. See for example, PCAST, " Report to the President and Congress on the Fourth Assessment of the National Nanotechnology Initiative. President's Council of Advisors on Science and Technology" (2012)

[46] OECD, "OECD, Science Technology, and Industry Scorecard," 2011.

[47] The U.S. President's Council of Advisors on Science and Technology (PCAST) in 2012 began using their work as well, which was identified to me by a member of the NSET Subcommittee as "good" data. Academics more generally rely on Porter, Shapira and Youtie, as they have produced the most comprehensive and methodologically rigorous metrics regarding nanotech activity, both in quantity and quality of patents (Philip Shapira and J. Youtie, "The Economic Contributions of Nanotechnology to Green and Sustainable Growth" (2012); Alan L. Porter et al., "Refining Search Terms for Nanotechnology," *Journal of Nanoparticle Research* 10 (5):715–728 (2007).

number of nanotechnology firms and employees in a country; patent applications and patents issued involving nanotechnology; and publications in scholarly journals on nanotechnologies.

Metrics Matter

Metrics of countries' technological competitiveness in emerging technologies shape national policy and the structure of international comparisons of competitiveness and technological developments, despite official recognition that the indices and measures used in calculating countries' position are problematic.[48] Estimates can vary wildly, as, for example, "in 2007, the market value for nano was either $11.6 billion or $147 billion, depending on whom you consult."[49] In 2001, the U.S. National Science Foundation predicted that by 2015 the world market for nanotech would reach $1 trillion, while Lux Research predicted that by 2020 nanotech products would have a $3 trillion market value. As of 2010, "current developments," according to NSF senior advisor for nanotechnology Mihail Roco, "presage a burgeoning economic impact: trends suggest that the number of nanotechnology products and workers worldwide will double every three years, achieving a $3 trillion market and 6 million workers by 2020."[50]

While projections indicate that expenditures on nanotechnology have risen to over $1 trillion, it is unclear what this actually means in terms of markets, innovation, products, and security applications. The data available are often drawn from Lux Research and Cientifica, and it is difficult to fully gauge what definitions and indicators give rise to their data as well as their interpretation of its significance. For example, Lux Research estimates market value of nanotech-enabled products based on the value of the finished product, rather than the nanotech component of the overall product. This can lead to substantial inflation of the actual market value of nanotech-enabled products. At the same time, Lux Research may significantly underestimate the impact of nanotech, if it is true that its data do not

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[48] As one senior member of the NSET Subcommittee put it, one has to be "very careful," as the data is "all over the map," and often compares "apples to olives." Anne Clunan, personal communication, May 31, 2013.

[49] ETC Group, "Geopiracy: The Case Against Geoengineering," 2010, p. 7.

[50] Mihail Roco, *Nanotechnology research directions for societal needs in 2020 retrospective and outlook*. Edited by Chad A. Mirkin, Mark C. Hersam and SpringerLink (United States] Dordrecht ; New York: United States : World Technology Evaluation Center ; Dordrecht ; New York : Springer, 2011a); Mihail Roco, "The long view of nanotechnology development: the National Nanotechnology Initiative at 10 years.(Editorial)(Report)," *Journal of Nanoparticle Research: An Interdisciplinary Forum for Nanoscale Science and Technology* 13 (2):427 (2011b), p. ii.

include electronics applications.[51] These data are an indicator, yet are only a small piece of a much larger and more complicated picture. Much nanotechnology is still largely in the research and development stage, and firms only began outpacing governments in their investments into this technology in 2006 or 2009. Given the large and often fatal "valley of death" between R&D and successful commercialization of new technologies, it is unclear what the existing data mean for national security, economic competitiveness, or nanotech governance, to which we now turn.

III. Nanotechnology Governance: Notable for Its Absence

The potential for nanotech and other emerging technologies to disrupt national industries and revolutionize military affairs raises the long-standing trade-off states face between sustaining economic innovation and maintaining national security and safety. The policy challenge entails encouraging the proliferation of nanoscience and nanotechnology and cultivating safe development and commercialization of nanotech-based products, while regulating in order to prevent malfeasant uses and mitigate against harmful effects of this technology. One of the most striking findings of this project is that, to date, there is a notable absence of concern over regulating nanotechnologies with military applications. Despite the significant military potential and possible toxicity of nanoparticles, there has been very little effort made to develop national or multilateral regulations that specifically regulate nanotechnologies.

Of the potential harms to public safety and national security that can arise from the civilian and military applications of nanotech, the primary focus of regulatory concern has been on environmental, health and safety effects. A very few have focused on the possibility of nano-targeted delivery of biological or chemical agents.[52] For others, the concern is less about devices produced, than the factories themselves, as scientists are working on molecular-scale components that spontaneously "self-assemble."[53] Nano-factories theoretically could produce complex products and even duplicate themselves, revolutionizing manufacturing (and the industrial capacity for war)

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[51] Mihail Roco says that Lux Research does not include electronics in its data collection. Anne Clunan personal communication with Mihail Roco, May 30, 2013.

[52] Jürgen Altmann, *Military nanotechnology : potential applications and preventive arms control*, (New York: Routledge, 2006); Margaret E. Kosal, *Nanotechnology for chemical and biological defense*, (New York: Springer, 2009).

[53] (Initiative); NATO, "Committee Reports Annual Session 179 STCMT 05 E - The Security Implications of Nanotechnology" (2005)

through exponential increases in efficiency, decreased failure rates, and radically lowered cost. A trillion computers would occupy a cubic centimeter. This has led some to call for preventive arms control regimes to govern nanotechnologies,[54] and others to advocate for an Inner Space Treaty, governing atomic and molecular space.[55]

This concern only grows as emerging scientific disciplines, particularly, nano-, bio-, and information technologies, converge to generate new trans-disciplinary research and applications.[56] As with biological weapons, almost all of the equipment and materials needed to develop dangerous nanotech-enabled weapons have legitimate uses in a wide range of scientific research and industrial activity. Examples include synthesized viruses (synthetic polio), delivery and dispersal, and manipulation of microbes. As a result, the governance challenge posed by nanotechnology is significant.

MULTILATERAL REGULATORY REGIMES FOR DUAL-USE TECHNOLOGIES

There is no current effort to create a multilateral regulatory regime specifically for nanotechnologies. This reflects the current understanding that nanotechnology does not pose significant mass destructive or disruptive potential.[57] Instead, existing formal and informal regulatory regimes that govern dual-use technologies are currently being extended to nanotechnologies. Nanotechnology's military applications with mass destructive or disruptive capabilities are most likely to arise in the chemical and biological spheres, which are increasingly indistinguishable from each other with the interdisciplinary development of synthetic biology.[58] The existing formal multilateral regimes in these

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[54] Jürgen Altmann, *Military nanotechnology : potential applications and preventive arms control*, (New York: Routledge, 2006)

[55] Sean Howard, "Nanotechnology and Mass Destruction: The Need for an Inner Space Treaty," *Disarmament Diplomacy* 65 (July-August 2002).

[56] Mihail C. Roco, Bainbridge, William S., Tonn, Bruce, Whitesides, George, "Convergence of Knowledge, Technology, and Society: Beyond Convergence of Nano-Bio-Info-Cognitive Technologies." World Technology Evaluation Center, Inc., 2013.

[57] Margaret E. Kosal, *Nanotechnology for chemical and biological defense* (New York:: Springer, 2009); OPCW, *Report of the Scientific Advisory Board on Developments in Science and technology for the Third Special Session of the Conference of the States Parties to Review the Operation of the Chemical Weapons Convention*. RC-3/DG.1 (October 29, 2012)

[58] Margaret E. Kosal, "Nanotechnology Threat Anticipation," unpublished presentation, September 3 2012; Margaret E. Kosal, "Strategy, Technology, and Governance: Shift of Responsibility from Nation-states to Individuals," Presentation prepared for delivery at the Society for the Study of

areas are the Chemical Weapons Convention, and the Biological and Toxin Weapons Convention. The Organization for the Prevention of Chemical Weapons (OPCW) in 2013 looked at nanotechnology implications for the Chemical Weapons Convention. It concluded that,

> As with advances in synthetic biology, nanotechnology has the potential for application to purposes prohibited by the Convention. The enhanced delivery of therapeutic drugs to their biochemical target could be exploited for the delivery of toxic chemicals. The concern for nanoparticles with significantly enhanced acute toxicity compared to larger particles has not been substantiated, although this is still under investigation. No nanomaterials are currently known to have an intrinsic toxicity that might make them attractive for use in chemical weapons. The risk to the Convention posed by nanomaterials is, therefore, currently regarded as low. The prevailing view of the [Scientific Advisory Board] is that *nanotechnology is unlikely to provide a dramatic improvement in the military utility of existing chemical agents, but it could be exploited in the development of new agents*.[59]

In terms of export control regimes, nations have been reluctant to significantly proscribe nanotechnology exports for competiveness reasons. U.S. companies, such as Zyvex Technologies, that were told that their CNT-enabled technology was subject to control under the U.S. munitions list (International Traffic in Arms Regulations (ITAR), administered by the U.S. Department of State), threatened to move their production overseas.[60] The significance of such threats prompted the U.S. President's Export Council to reject unilateral controls on any nanotechnologies without "clear military and national security applications," stating that export controls would have to be "multilateral in order to be effective."[61]

Nanoscience and Emerging Technologies 5th Annual Meeting, Boston, MA, October 27-29, 2013, p.15.

[59] OPCW, *Report of the Scientific Advisory Board on Developments in Science and technology for the Third Special Session of the Conference of the States Parties to Review the Operation of the Chemical Weapons Convention*. RC-3/DG.1 (October 29, 2012); 14. Emphasis added.

[60] Margaret E. Kosal, "Nanotechnology Threat Anticipation," unpublished presentation, September 3, 2012.

[61] J.W. Marriott, Jr. *President's Export Council Letter to President Bush Concerning Export Controls on Nanotechnology*, 2006. Cited in Jacob Heller and Christine Peterson, "Nanotechnology: Maximizing Benefits, Minimizing Downsides," *Nanoscale: Issues and Perspectives for the Nano Century,* pp. 83-96, edited by Nigel M. de S. Cameron and M. Ellen Mitchell. (Hoboken, NJ: Wiley & Sons, 2007), p. 91; *Washington Trade and Tariff Newsletter* 25: 48 (December 5, 2005), p. 1.

The general concern over eliminating U.S. national competitiveness in nanotechnologies has led to the reorganization of U.S. export controls under the Export Control Reform Initiative, such that almost all dual-use technologies, including nano-enabled ones, as of October 2013, now fall under the purview of the Department of Commerce Bureau of Industry and Security's Commerce Control List (CCL). According to the Department of State,

> The CCL includes the following:
> - Items on Wassenaar Arrangement Dual-Use List
> - Nuclear-related dual use commodities (compiled in the Nuclear Suppliers Group's Nuclear Referral List)
> - Dual-use items on Missile Technology Control Regime List
> - CW Precursors, biological organisms and toxins, and CBW-related equipment on the Australia Group lists
> - Items controlled in furtherance of U.S. foreign policy and other objectives, including anti-terrorism, crime control, Firearms Convention, regional stability, UN sanctions, and short supply reasons
> - Unlisted items when destined for specified end-uses or end-users (catch-all controls).[62]

The Wassenaar Arrangement Dual-Use List contains two nanotech items: nanocrystalline alloy strips and nano-imprint lithography tools; it also lists 14 instances of equipment producing items at 200 nm or less. There is no mention of nanotechnology on the Wassenaar Munitions List.[63] The Russian Federation lists the same two items, and a slightly broader listing of nanoscale equipment.[64] The Nuclear Suppliers Group lists one dual-use nanoscale item, Alexandrite lasers, in its *Guidelines for Transfers of Nuclear-Related Dual-Use Equipment, Material and Related Technology*.[65] The Australia Group lists also do not specifically refer to nanotech, though they do specify genetically modified organisms or chemically synthesized genetic elements associated with the pathogenicity of microorganisms and toxins on their lists.[66] The U.S. reliance on the CCL has led to criticism that this new laxity in U.S.

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[62] U.S. Department of State, "Overview of U.S. Export Control System." June 15, 2014.
[63] Wassenaar Arrangement, *List of Dual-Use Good and Technologies and Munitions List.* April 12, 2013.
[64] Russian Federal Technological and Export Control Service (FSTEC), *Spisok Tovarov i Tekhnologii Dvoinnovo Naznacheniia, Kotorie Mogut Byt' Ispolsovanyi pri Vooruzhenii i Voennoi Tekhniki i v Otnoshennii Kotoryikh Osushchestvliaetsia Eksportnyi Kontrol* (List of Dual-Use Goods and Technologies Capable of Use in Weapons and Military Equipment and Subsequently Subject to Export Control). December 17, 2011.
[65] IAEA, Guidelines for Transfers of Nuclear-Related Dual-Use Equipment, Material and Related Technology. INFCIRC/254/Rev.1/Part 2 Annex, July 1992.
[66] Australia Group, C*ommon Control Lists*. June 15, 2014.

export controls has "the potential to exacerbate weapons proliferation and undermine American security."[67]

Different Approaches to Nanotech Risk and Regulatory Implications

As previously noted, the lack of consensual definitions means that the data collected and used to estimate nanotechnology's economic, security, and safety potential and risk is often based on different meanings and measures of nanomaterial, nanoparticle, and nanotechnology. Questionable data, competing definitions, different risk perceptions, and economic competition significantly complicate efforts to find national, let alone international standards upon which to base nanotechnology regulations. These factors have to date prevented the establishment of global statistical definitions of nanomaterials on which to base private commercial regulatory standards and the establishment of consensual global norms over nanotechnology governance. As a result, countries are pursuing different approaches to national regulation of nanotechnologies, based in large measure on whether to apply a "wait-and-see" or precautionary approach to the potential risks arising from nanotechnologies and their manufacture.

Currently, the biggest principled difference in global regulation lies between the European Union and the United States. "Even though the US and the EU are not consistent in the use of precaution in domestic regulation, they have come to occupy opposing positions in international regulatory debates. While the US has repeatedly insisted that regulatory trade restrictions should be based on 'sound science' in line with WTO law, the EU has pushed for the global expansion of precautionary standards and a re-balancing of the relationship between WTO rules and environmental policies in favor of the latter."[68]

The EU has been much more proactive than the United States in establishing environmental, health and safety regulations, particularly through the 2007 law regulating chemicals Registration, Evaluation, Authorization and Restriction of Chemicals **(**REACH). In contrast, U.S. regulation has been based on a thirty-year-old law, the Toxic Substances Control Act (TCSA). The EPA in 2006

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[67] David Fitzgerald, "Leaving the Back Door Open: How Export Control Reform's Deregulation May Harm American Security," *North Carolina Journal of Law and Technology* 15, Online Edition: 65-99. (2014), p. 75.

[68] Robert Falkner and Nico Jaspers, "Regulating Nanotechnologies: Risk, Uncertainty and the Global Governance Gap," *Global Environmental Politics* 12(1): 30-55. (2012), p. 34.

decided that nanosilver constitutes a pesticide and requires registration. In 2008, it ruled that CNTs constitute a new chemical under the TCSA. However, in 2007, the Food and Drug Administration (FDA) rejected nano-specific labeling requirements.

The EU definition of nanomaterial discussed earlier does not distinguish between engineered nanomaterials, which have an identifiable producer that can be addressed, and naturally occurring nanomaterials, including diesel soot or wood smoke, which are harder to trace and thus regulate. This has led to concerns over regulatory requirements, as it may change the requirement from one where only engineered nanoparticles be labeled as nanomaterials to one that includes products containing naturally occurring nanoparticles.[69] In its approach, the EU appears to be relying on the precautionary principle with respect to nascent nanotechnology regulation. The U.S. definition of nanomaterial, in contrast would exclude naturally occurring nanomaterials from regulation, an approach presently taken by the U.S. FDA.[70] The United States generally is following a piece-meal approach to nanotech regulation. In contrast to the EU, the USG has been more risk-acceptant of commercial nanotech-applications, though this approach successfully challenged.[71]

The International Organization for Standardization (ISO) plays a central role in establishing the commercial standards that allow product certification. Without a set of agreed nanotech standards, countries and industries are presently engaged in a competition to set these standards in ways that advantage their domestic industries.[72] These actors have also focused on voluntary governance mechanisms to avoid the introduction of nano-specific regulations that might impede innovation and competitiveness.

BOTTOM-UP REGULATION OF NANOTECHNOLOGY

In general, the existing atmosphere regarding regulation of nanotechnology stresses individual and corporate responsibility, rather than government intervention. In part because of the immense difficulties in defining, monitoring and verifying the development, manufacturing, transfer and use

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[69] Nanowerk, "Definition of the Term Nanotechnology," 2013.
[70] U.S. Food and Drug Administration, "Considering Whether an FDA-Regulated Product Involves the Application of Nanotechnology," 2011.
[71] Carolyn R. Davis, Stanley Goos, and Anne M. Schneiderman, "Ninth Circuit Vacates EPA's Approval of Nanosilver-based Pesticide," Lexology.com, November 26, 2013.
[72] Anne L. Clunan, personal communication with senior NSET subcommittee member, Washington, DC, May 31, 2013.

of these emerging technologies—characteristics that nanotechnologies share with biotechnologies--there is little effort underway to introduce government regulation aimed at limiting dual-use items. Unlike the case of chemical weapons, where the chemical industry was a key participant in the drafting of the Chemical Weapons Convention, in biotechnology, there has been no such collaborative attitude.[73] Instead, efforts have been made since 1975 to develop voluntary codes of conduct for industry and academics to self-regulate and self-censor.[74] The same currently applies to nanotechnology. Corporations and some scholarly enthusiasts have championed these private regulatory regimes in order to avoid government involvement.[75]

Several voluntary frameworks currently exist in the nanotech field. These are *The Nano Risk Framework* developed by the Environmental Defense Fund and DuPont; the *Nano Code* developed in the United Kingdom; the U.S. Environmental Protection Agency's Nanoscale Materials Stewardship Program; the U.K. government's *Voluntary Reporting Scheme for Engineered Nanoscale Materials*; the commercially driven *Assured Nano* accreditation scheme; the 2008 EU Commission Recommendation on a Code of Conduct for Responsible Nanosciences and Nanotechnologies Research.[76] "This voluntary code of conduct aims to guide the actions of member states in the promotion of innovation and research, particularly regarding 'integrated, safe and responsible nanosciences and nanotechnologies research in Europe for the benefit of society as a whole'."[77]

The cumulative effect of these efforts is that normative and regulatory frameworks surrounding nanotechnology are increasingly viewed as the responsibility of individual corporations and

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[73] Anne L. Clunan, "Building Information Networks for Biosecurity," *Terrorism, War or Disease? Unraveling the Use of Biological Weapons,* pp. 293-310, Anne L. Clunan, Peter R. Lavoy and Susan B. Martin, editors. (Palo Alto: Stanford University Press, 2008).

[74] Margaret E. Kosal, "Strategy, Technology, and Governance: Shift of Responsibility from Nation-states to Individuals," Presentation prepared for delivery at the Society for the Study of Nanoscience and Emerging Technologies 5th Annual Meeting, Boston, MA, October 27-29, 2013, pp. 10-12

[75] Tim Büthe and W. Mattli, *The New Global Rulers: The Privatization of Regulation in the World Economy* (Princeton: Princeton University Press 2011); Stephen M. Maurer, editor, *WMD Terrorism: Science and Policy Choices* (Cambridge, Mass: MIT Press, 2009); Stephen M. Maurer, "Five Easy Pieces: Case Studies of Entrepreneurs Who Organized Private Communities for a Public Purpose" (November 1, 2010), Goldman School of Public Policy Working Paper No. GSPP10-011.

[76] Daniel J. Fiorino, *Voluntary Initiatives, Regulation, and Nanotechnology Oversight: Charting a Path*, Project on Emerging Nanotechnologies, 2010; pp. 28-29.

[77] Kirsten L. Rodine-Hardy, "Big Government for Small Technology: European Regulation for Nanotechnology," Paper prepared for delivery at the European Consortium of Political Research Conference in Dublin, Ireland June 17 – 21, 2010.

scientists. Governance of emerging technologies is devolving downwards, with very little interest in developing international norms or agreements to govern nanotech production and use.[78] This attitude stems largely from perceived economic imperatives facilitate innovation and commercialization in the three high tech sectors seen as critical to technological leadership and competitiveness in the 21st century: nanotechnology, biotechnology, and information and communications technology. The next section of the report describes the global landscape of nanotechnology R&D, a picture that highlights the extent to which how nanotechnology has captured the imagination of national governments as a key to progress.

IV. The Global Landscape of Nanotechnology R&D

Over sixty countries adopted national nanotechnology initiatives between 2000 and 2012 (see Figure 1, p. 27). These countries range from advanced industrial countries to emerging markets. The adoption of country-specific, coordinated nanotechnology R&D programs began at the turn of the millennium, with the United States' creation of the National Nanotechnology Initiative (NNI) in 2000. In the same year, Sweden created a nanotechnology initiative. A veritable explosion of NNIs happened immediately following these two countries, with twelve nations establishing some sort of national program in 2001. Countries as diverse as Luxembourg, Estonia, China, Canada, and Japan developed new programs. From then on, as shown in Figure 1, a steady stream of countries created national nanotechnology programs, with the most recent adopters being Australia (2010) and Iraq (2012).

Why the Rapid Global Diffusion of National Nanotechnology Initiatives?

The diffusion of nanotechnology initiatives occurred within a very condensed period of time. In a period of 12 years, more than 60 countries created nanotech initiatives. Why do we see this rapid adoption of NNIs across such a diverse group of countries?

Conventional wisdom in political science and business focuses on the role of political and economic power in the international system, or at least market power, and would expect large countries to be leaders in the adoption of nanotechnology. One would expect a small group of high-income

[78] Margaret E. Kosal, "Strategy, Technology, and Governance: Shift of Responsibility from Nation-states to Individuals," Presentation prepared for delivery at the Society for the Study of Nanoscience and Emerging Technologies 5th Annual Meeting, Boston, MA, October 27-29, 2013, p. 15.

adopters at the beginning, followed by a period of low activity, then a wave of adoption some years later, with laggards joining in after the trend has caught on. The trend for nanotech, in contrast, seems to be a consistent and steady rise in adoption.[79] The patterns of which countries are leading the charge in nanotech R&D and when they adopt national nanotechnology initiatives are anomalous in terms of expected technology diffusion patterns, as well as the diffusion of liberal economic policies.[80] There is very little correlation at all in terms of size of government investment in nanotech R&D and the timing of adopting a new national nanotechnology initiative. Nor is there a readily identifiable leader/laggard distinction among nations; instead there is a growing trend that transcends traditional geographic or political expectations. For example, while it makes sense substantively that Japan, the United States, and Sweden adopted national nanotechnology initiatives in 2000, it is not obvious why such different small countries as Singapore, Estonia, Ireland, and Romania adopted programs in the following year, or why Armenia, Pakistan, and Belarus adopted programs in 2002. Further, Germany has one of the largest nanotechnology markets, yet did not adopt a national nanotechnology initiative until 2006, after the EU framework was adopted. Many small countries with very little political power and no market power (e.g. Armenia, Estonia, Romania) adopted nanotechnology initiatives in the earliest phases. Geopolitical power does not seem to be an easy or obvious answer to why so many countries adopted national nanotechnology initiatives in such a short space of time.

The diverse ways that countries have used nanotechnology initiatives to signal to the global community could explain the unusual diffusion pattern. Unlike other technological regulations and initiatives, nanotechnology has been is hailed as the basis for a new technological and military revolution.[81] Political elites widely accept cutting-edge technology as a fundamental source of long-

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[79] Clayton Christensen, *The innovator's dilemma : when new technologies cause great firms to fail* (Boston Mass.: Harvard Business School Press, 1997); Clayton Christensen, "The Ongoing Process of Building a Theory of Disruption.(Dialogue on the Effects of Disruptive Technology on Firms and Industries)," *Journal of Product Innovation Management* 23 (1):39 (2006)

[80] Everett M. Rogers, *Diffusion of Innovations*, 4th ed (New York: Free Press, 1995); Kirsten Rodine-Hardy, *Global markets and government regulation in telecommunications* (Cambridge: Cambridge University Press, 2013)

[81] C. Jordan, N. Kaiser, and V. Moore, "Nanotechnology Patent Survey: Who Will Be the Leaders in the Fifth Technology Revolution?" *Nanotechnology Law & Business* 9 (Fall 2012): 122-13; M. Knell, "Nanotechnology and the Sixth Technological Revolution," *Nanotechnology and the Challenges of Equity, Equality, and Development*, edited by SE. Cozzens and JM Wetmore (Springer, 2011)

term economic growth and national advantage for economic and military prowess. Inherent in their concepts of "technological revolutions" and "disruptive technology" is the widespread belief that technology drives historical changes in economy, society, politics and war. "As the next major technology wave," according to some, "nanotechnology will be revolutionary in a social and economic as well as a scientific and technological sense."[82] For many, the political corollary is that states that are able to capture a technological lead will gain significant wealth and military power over other states. The United Nations has identified nano-, bio- and information technologies as the key platform technologies for growth and development.[83] The potential for a nanotechnological revolution has inspired grand claims about its promise for development and progress.

Such promises have distorted the diffusion process, encouraging small, less developed countries to jump on the bandwagon, hoping it will help them catch up. According to a leading Latin American expert on nanotech, once the United Nations announced in 2005 that nanotech was a key technology for development, all the Latin American countries adopted a NNI. For them, it is an issue of developmental aspirations and prestige.[84] Others see nanotechnology as a security issue, an issue of political power or prestige. For countries, such as Brazil, Russia and India, adopting a national nanotechnology initiative seems to reflect a strategic signal to global markets and political players that a country is seriously considering its role in the world, and acting to pursue its own strategic interests and international prestige. In contrast, Germany has minimized the military applications of nanotechnology, focusing instead on its commercial promise, suggesting to other global players that it does not intend to use nanotechnology for offensive capabilities. China appears to be much more focused on the economic growth potential of nanotech than on its military applications.[85] Still others are less easily swayed by the grand promises of nanotechnology. Many see it through multiple lenses. A country that sees nanotechnology as the long-awaited technological

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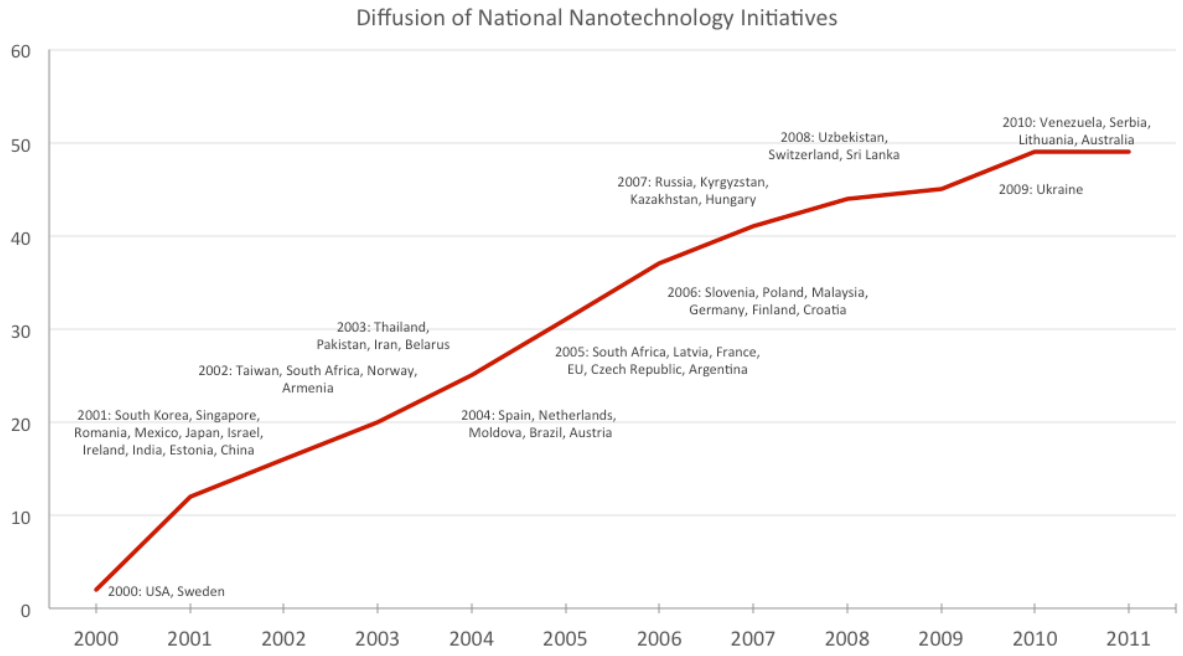
[82] P. Singer., F. Salamanca-Buentello, and A. Daar, "Harnessing Nanotechnology to improve global equity: the less industrialized countries are eager to play an early role in developing this technology; the global community should help them," *Issues in Science and Technology* 21 (4), 2005.
[83] C. Juma and L. Yee-Cheong, "Innovation: Applying knowledge in development," UN Millennium Project Task force on Science, Technology and Innovation (2005)
[84] Anne Clunan, personal communication with Noela Invernizzi, Boston, Mass., October 25, 2013.
[85] Anne Clunan, personal communication with senior member of the NSET subcommittee, Washington, D.C., May 31, 2013. See also the report's case studies of China.

revolution and key to modernity will approach adoption differently than a country that sees it as only an issue of security or hardly an issue at all.

Figure 1. Worldwide spread of national nanotechnology initiatives, 1990-2014



Source: Kirsten Rodine-Hardy Research Team 2014; original dataset compiled from publicly available sources.

The report next focuses on some of these different approaches, first with a brief snapshot of Brazil, China, India, and Russia, then takes a closer look at European Union trends and the EU's two biggest nanotech markets, Germany and the United Kingdom, and examines in depth the case of China.

A Quick Look at Nanotech Adoption in Brazil, China, India and Russia

As of 2011, China, India, and Russia all had "full-fledged nanotechnology policies involving dozens of institutions, hundreds of research and education centers and large amounts of R&D spending."[86] Brazil has also made a concerted investment in nanotechnology.

Brazil established its national nanotechnology initiative in 2004-2005. Brazil has declared nanotechnology to be one of eleven areas for strategic government investment. The Ministry of Science, Technology and Culture invested an average of $5 million a year in nanotech over the course of 2004-2008.[87] According to Kay and Shapira, "Brazil, although perhaps a third-tier country in nanotechnology output at the worldwide level, is clearly the leader in terms of nanotechnology publications in the [Latin American] region. Brazil contains about one-third of all scientists in Latin America (UNESCO 2005) and contributes more than 50% of the continent's nanotechnology research output."[88] Brazil's government has focused attention on technology transfer, in order to increase the number of patents associated with nanotech research.[89] According to experts, in Brazil there is a "fever" regarding patents, and the government's is pushing universities and corporations to establish nanotech patents purely for prestige, as they have no commercial application.[90] Nanotechnology is "now the high science in Brazil", according to Paulo Martins. As of 2012, there were 17 nanotech networks established in Brazil, and eight national labs, over 2,500 researchers and 3,000 graduate students were focused on nanotech. The Brazilian government reportedly views

[86] Evegeny A. Klochikihin, "Public policy instruments in (re)building national innovation capabilities: cases of nanotechnology development in China, Russia and Brazil," Atlanta Conference on Science and Innovation Policy, Atlanta, GA, 2011.
[87] E. O'Rourke and M. Morrison, "Challenges for Governments in Evaluating Return on Investment from Nanotechnology and Its Broader Economic Impact," *OECD Background Paper* (2012)
[88] Luciano Kay and Philip Shapira, "The Case of Brazil," *Nanotechnology and the Challenges of Equity, Equality and Development*, edited by Susan E. Cozzens and Jameson Wetmore (Springer, 2011).
[89] E. O'Rourke and M. Morrison, "Challenges for Governments in Evaluating Return on Investment from Nanotechnology and Its Broader Economic Impact," *OECD Background Paper*, (2012)
[90] Anne L. Clunan, personal communication with Luciano Kay and Noela Invernizzi, Boston, Mass, October 28, 2013.

nanotechnology investments as imperative for increasing Brazil's S/T base and its international competitiveness.[91]

CHINA has designated nanotech R&D as one of twelve "mega-projects" under its Medium and Long Term Development Plan 2006-2020.[92] China has stepped up publishing and patenting in nanotechnology in order, by some accounts, to increase their ranking in global nanotechnology indices.[93] The head of the Chinese Academies of Science is a nanotechnology scientist, and China has "come up very quickly academically, its labs are very good," according to a senior U.S. official.[94] A much closer look at China's nanotechnology programs is provided later in the report.

INDIA established a Nano Science and Technology Initiative in 2001, but with modest support and aims. In 2005, an Indian Defense Research and Development Organization (DRDO) official stated that India was set to become a "leader in nanotechnology within the next five to ten years."[95] In 2007, India launched a new Mission on Nano Science and Technology (Nano Mission) under the Department for Science and Technology, with a budget of approximately $145 million over five years. The Nano Mission funds basic research and development equally, and focuses on water sanitation and drug delivery.[96] President A.P.J. Abdul Kalam, himself a rocket scientist, was and remains one of the chief promoters of India's investments in nanotech; in 2009 he stated that, "we believe that nanotechnology would give us an opportunity, if we take an appropriate and timely action to become one of the important technological nations in the world."[97] India is one of very few countries to highlight military applications of nanotech, though its primary emphasis has been on development. The Scientific Advisor to the Indian Minister of Defense highlighted some of these

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[91] Paulo Roberto Martins, "Science for Production x Science for Impacts: Brazilian Development of Nanotechnology in Section XXI," Presentation prepared for delivery at the Society for the Study of Nanoscience and Emerging Technologies 5th Annual Meeting, Boston, MA, October 27-29, 2013.
[92] E. O'Rourke and M. Morrison, "Challenges for Governments in Evaluating Return on Investment from Nanotechnology and Its Broader Economic Impact," *OECD Background Paper*, (2012)
[93] Anne Clunan, personal communication with Margaret E. Kosal, April 2, 2013.
[94] Anne Clunan, personal communication with senior member of the U.S. NSET Subcommittee, May 31, 2013.
[95] The Hindu, "India becoming a Pioneer in Nano Technology." *The Hindu*, 2005.
[96] E. O'Rourke and M. Morrison, "Challenges for Governments in Evaluating Return on Investment from Nanotechnology and Its Broader Economic Impact," *OECD Background Paper*, edited by (2012)
[97] A.P.J. Abdul Kalam, "Dimensions of Nano Science and Technology," Special Address at Nanotechnology Workshop, University of Hyderabad, November 14, 2009.

applications in 2012: "Nanotechnology should lead to higher protection, more lethality, longer endurance and better self-supporting capacities of future combat soldiers. Substantial advantages are expected to be gained, which include threat detection, novel electronic display and interface systems, as well as a pivotal role for the development of miniaturized unmanned combat vehicles and robotics. Nanotechnology will also enable small portable sensor systems capable of identifying chemical, biological, nuclear, radiation, or explosive threats."[98]

RUSSIA, one of the last entrants in the nanotech cascade, dropped a figurative as a well as literal "nano-bomb" in 2007, with the establishment of a $9 billion state-funded nanotechnology initiative, and the detonation of a thermobaric "father of all bombs" that the Russian government claimed was the first nano-weapon.[99] The Russian nanotech program has been pushed at the highest levels, beginning with President Vladimir Putin. "In his [2007] annual address to the Federal Assembly, Putin singled out nanotechnology as the locomotive of Russia's scientific and technological development strategy."[100] Former Defense Minister and then First Deputy Prime Minister Sergei Ivanov, in noting that half of Russian scientists work in the military industrial complex and seventy-percent of scientific production is military in nature, said in 2007 that nanotechnology "can drastically change all of our perceptions about modern warfare."[101] Russia has also established a government-controlled nanotechnology venture capital firm, RUSNANO, to invest in and acquire nanotechnology start-ups around the world. Russia, more than any other country, emphasizes the offensive as well as defensive military applications of nanotech, perhaps because military might is widely viewed as the key source of Russia's international status.[102]

The Russian Ministry for Science and Education issued a development program for Russian nano-industries in 2007 that was create a competitive nanotech R&D sector by 2011. This sector would "make it possible for the Russian Federation to achieve scientific-technical parity with the developed nations in the world. By 2011, new nanotechnology products were to have been developed that

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[98] DRDO, "Nanotechnology Applications for Defence Applications," *DRDO Newsletter* 32:11 (November 2012)
[99] F. Westerlund, *Russian Nanotechnology R&D: Thinking Big about Small Scale Scie*nce (Stockholm: Swedish Defense Research Agency, 2011), p. 34.
[100] F. Westerlund, *Russian Nanotechnology R&D: Thinking Big about Small Scale Scie*nce (Stockholm: Swedish Defense Research Agency, 2011), p. 35.
[101] "Military Industry Makes Up 70% of Russian Science Production," RIA Novosti, April 19, 2007.
[102] (Clunan 2009).

could be industrially produced within two to three years, and an efficient system for their commercialization established. The ultimate goals were to have laid the foundations for a large-scale increase in the production volumes of new types of nano-industry products by 2015, and to have established Russian companies in the global high technology market."[103] The development program also laid out publishing and patenting targets. Nano-electronics, engineering, materials (for energy, space, construction use), biotech and security systems were designated as priority R&D areas.[104] The Russian Federation in 2011 devoted the most government and higher education expenditures to nanotechnology R&D, at 5.6% or USD729 million PPP.[105] These expenditures, together with RUSNANO's activities, have made Russia a highly visible player in the nanotechnology field. While this highly visible push into nanotechnology has placed Russia in the top ten government sponsors of nanotech R&D, the quantity and quality of Russian nanotech (and more generally) patenting and publications remain low.[106]

In marked contrast to Russia, where the defense sector has long been the source of Russian innovation, nanotechnology and security in the European Union present a more complicated picture. Traditional realist assumptions, which emphasize the importance of relative national power and the necessity for strong military capacity, do not capture the shifting security dynamics in the EU nor the regulatory frameworks that are evolving around dual-use nanotechnologies. The next section turns to the relationship between nanotechnology innovation and security in Europe; it begins with the European Union then attends to the two largest nanotechnology markets in Europe: Germany and the United Kingdom.

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[103] F. Westerlund, *Russian Nanotechnology R&D: Thinking Big about Small Scie*nce (Stockholm: Swedish Defense Research Agency, 2011), pp. 39-40, 46.
[104] F. Westerlund, *Russian Nanotechnology R&D: Thinking Big about Small Scie*nce (Stockholm: Swedish Defense Research Agency, 2011), pp. 43-44.
[105] OECD, Regulatory Frameworks for Nanotechnology in Foods and Medical Products: Summary Results of a Survey Activity, *OECD Science, Technology and Industry Policy Papers No. 4* (Paris, France: OECD Publishing, 2013).
[106] Evgeny A. Klochikhin, "Innovation System in Transition: Opportunities for Policy Learning between China and Russia," *Science and Public Policy* 40 (2013), pp. 666-667.

THE EUROPEAN UNION

Security policy in Europe has taken on a distinctly regional rather than national framework, through the establishment of agreements such as the EU Common Security and Defense Policy and institutions such as the European Defence Agency (EDA). Over the past three decades, there has been a shift in regulatory authority away from states towards governance of military and security concerns at the European and international levels through participation in NATO and the EU. This trend of increasingly limited national authority can be reflected in the reduced defense expenditures of EU countries. Since the 1960s, defense spending as a percentage of GDP across EU states has decreased by nearly 70% and now averages around 2% of GDP.[107] Even amongst the most powerful and influential states in Europe, including the United Kingdom, France, and Germany, there has been a significant reduction in national defense spending and an increased focus on regional security.

Several European-wide initiatives have been proposed which bring together member states and EU institutions in a collaborative effort to promote the R&D of nanotechnology for security purposes. In 2006, European governments in collaboration with the EDA established a two-year Joint Investment Programme (JIP) to promote collaborative R&D efforts on emerging defensive technologies, including nanotechnologies. In 2008, a second two-year JIP was agreed upon which included advisors from eleven EU member states and was funded by a common budget of €15.5 million.[108] These efforts represent a multilateral approach to defense that relies upon the contributions and commitments of various members and is focused upon regional rather than strictly national security concerns. An important feature of these programs has been an emphasis on the expansion of nanotechnology markets not only for security, but also for commercial purposes, including the development and production of new nano-material structures, novel medicines and therapeutic treatments, and alternative energy sources. Since many of these products have potential dual-use applications, the growth of a diversified nanotechnology market in Europe is seen as beneficial from both an economic and security perspective.

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[107] Frédéric Mérand, *European Defence Policy: Beyond the Nation State* (Oxford University Press, 2008), 151.

[108] EDA, "European Defence Agency News: EDA Establishes New Joint R&T Programme on Disruptive Defence Technologies." (2008).

In a 2012 roundtable on the strategic importance of Europe's nano-electronic sector, Michael Sieber, the assistant director for research and technology at the EDA stated, "without the nano-electronics sector there would be no viable defense sector, and without defense, investment in nano-electronics would not be feasible."[109] This statement highlights the interdependencies that exist between security and economic concerns at the European level. According to the EDA, in order to ensure the development and production of the next generation of nano-electronics, used for a range of defense purposes including satellites, communications, and computing, it is critical to establish a sustainable and globally competitive nanotechnology market in Europe.[110] Fostering a strong nanotechnology sector would help to ensure continued investment in R&D and promote innovations critical for both economic growth and regional defense. The EDA has also funded projects to establish specialized European supply chains to alleviate concerns about access to critical resources, which may be subject to export restrictions, and the supply of vital materials that are produced at limited volumes.[111] To achieve this objective of a thriving EU nanotechnology market requires strategic planning and commitment on behalf of a range of stakeholders at multiple levels including EU policymakers, government representatives, and firms.

Germany and the United Kingdom: Divergent National Styles of Nano Innovation and Security

By Ian McManus

The complex relationship between nanotechnology security and economic concerns plays out at the country as well as the European level, shaped by longstanding national regulatory styles. States hold different policy preferences and attitudes about the role of the state in defining security and economic policies. This study focuses on the two biggest markets for nanotechnology in the European Union, Germany and the United Kingdom, to evaluate how different national histories affect nanotech policy. These differences are based on distinct historical experiences, political institutions, and economic structures which shape actor preferences. Examining these national differences from a comparative perspective provides a useful overview of the evolving nature of nanotechnology governance concerns and helps to explain the different approaches states have

[109] EDA, "European Defence Agency News: Nanoelectronics' Importance for Defence." (2012)
[110] Ibid.
[111] Ibid.

taken to promote the R&D of dual-use technologies. Despite dissimilar national security positions, the German and UK cases highlight a significant shift away from direct military spending on defense toward market-driven strategies of nanotechnology R&D for commercial purposes, with profound implications for the security realm.

Germany

German security policy has been deeply shaped by the country's historical experience and its political institutions, which have placed significant constraints on military efforts and defense spending. Since the end of World War II, the German policy position on security issues has reflected a desire for multilateralism and international cooperation. In terms of international security policy, Germany has largely been in favor of greater European integration and regional decision-making.[112] This position is reflected in public support for an EU Common Defence and Security Policy that is significantly higher in Germany than in other member states, such as the United Kingdom.[113] Even the concept of domestic policy based on "national interest" remains deeply controversial within Germany, as it implies that German interests might differ or be at odds with European or global interests. Reflecting historical experience, the German public has also remained wary of security policies that utilize offensive strategies that might allow Germany to be perceived as an aggressor.

In addition to the influence of historical antecedents and public opinion pressure, German security policy is further constrained by its federal institutions and by its consensus-driven political system. There are numerous checks and balances within the German federal government that limit the power of the executive and which result in greater consensus-building in defining foreign and security policies.[114] The result is an inclusive decision-making process with a high degree of local and regional representation in national-level legislation policies.[115] In addition to the involvement of various stakeholders in the legislative process, the executive branch is also responsive to the needs

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[112] J. Junk and C. Daase, "Strategic Cultures in Europe: Security and Defence Policies Across the Continent." edited by H. Biehl, B. Giegerich and A. Jonas. (Springer, 2013).
[113] Frédéric Mérand, *European Defence Policy: Beyond the Nation State* (Oxford University Press, 2008).
[114] Patrick H. O'Neil, K. Fields, and D. Share, *Cases in Comparative Politics*. 3rd ed (W.W. Norton, 2010); Kate O'Neill, *Waste Trading Among Rich Nations: Building a New Theory of Environmental Regulation* (Cambridge, MA: MIT Press, 2000b).
[115] Vivien A. Schmidt, "Procedural democracy in the EU: the Europeanization of national and sectoral policy-making processes," *Journal of European Public Policy* 13 (5):670-691 (2006).

and interests of various constituencies. The German Chancellor is openly constrained by coalition politics and the need to appeal to a broad base of interests.

All of these factors result in a German security policy that can be characterized as passive, reactive, and more oriented toward actively seeking international cooperation through multilateral means. Despite its economic strength and active leadership role within the EU on social and economic policies, when it comes to foreign and security policies Germany takes on a more neutral role relying on NATO and EU institutions to define policies. This has led some European allies to view Germany as a "reluctant hegemon" within the EU security sector, whose capacities are greater than the country's ambitions to define security policies.[116]

This preference for multilateral cooperation and the international governance of security issues has prevailed in debates over nanotechnology regulations. In 2004, the German Parliament's Committee for Education, Research, and Technology Assessment of the Consequences of Technology released a report which included possible military uses and security risks of nanotechnology. The report concluded that immediate short-term security risks of nanotechnology seem unlikely, but emphasized the need for strengthened international cooperation to ensure responsible development and production and the benefit of multilateral initiatives, similar to measures governing small arms and chemical weapons, to limit possible misuse.[117] In other words, German government officials highlighted the importance of international regulatory regimes over domestic governance strategies to address the potential issues of nano-security. Unsurprisingly given this position, whereas some countries, such as the United States, allocate portions of their defense budget specifically to the development of nanotechnology for security, the German government does not fund the R&D of nanotechnology for military applications, even for defensive purposes.

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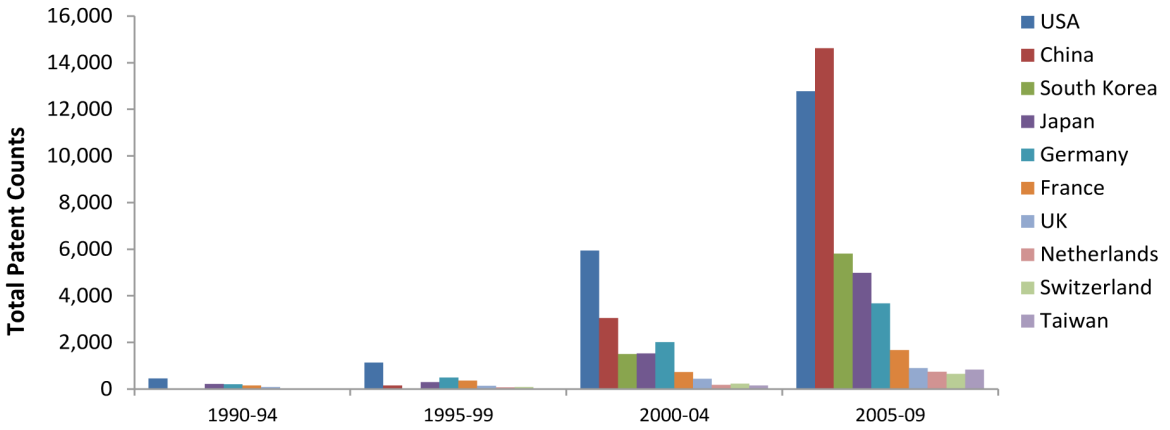
[116] William E. Paterson, "The Reluctant Hegemon? Germany Moves Centre Stage in the European Union," *Journal of Common Market Studies* (2011).
[117] NATO, "Committee Reports Annual Session 179 STCMT 05 E - The Security Implications of Nanotechnology" (2005).

Figure 2. Counts of patent applications in nanotechnology in PATSAT, by year and assignee country, 1990-2009

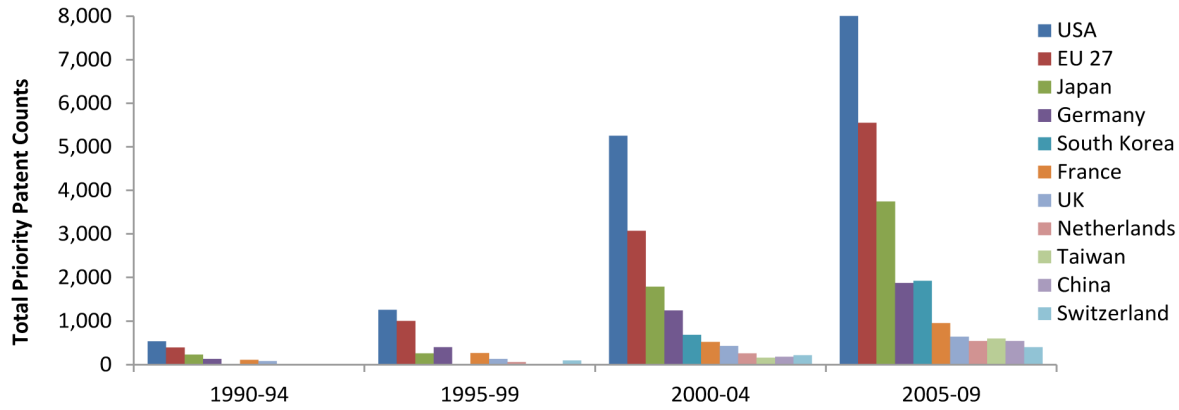


Source: L. Kay, P. Shapira, J. Youtie, and A. L. Porter, Program on Nanotechnology Research and Innovation System Assessment Georgia Institute of Technology, Atlanta, Georgia, with support from the National Science Foundation (NSF) through the Center for Nanotechnology in Society (Arizona State University; Award No. 0937591) [Data as of January 2010]. PATSTAT stands for the Patent Statistical Database, which is maintained by the European Patent Office.

Note: Based on definition of "nanotechnology" by A. L. Porter, J. Youtie, P. Shapira, and D. Schoeneck, "Refining Search Terms for Nanotechnology," *Journal of Nanoparticle Research*, 10 (5): 715–728.

Source: Reproduced from President's Council of Advisors on Science and Technology (PCAST) 2012 Report, p. 6.

Figure 3. Counts of priority patent applications in nanotechnology, by year and assignee country, 1990-2009



Source: L. Kay, P. Shapira, J. Youtie, and A. L. Porter, Program on Nanotechnology Research and Innovation System Assessment Georgia Institute of Technology, Atlanta, Georgia, with support from the National Science Foundation (NSF) through the Center for Nanotechnology in Society (Arizona State University; Award No. 0937591) [Data as of January 2010]. PATSTAT stands for the Patent Statistical Database, which is maintained by the European Patent Office.

Note: Based on definition of "nanotechnology" by A. L. Porter, J. Youtie, P. Shapira, and D. Schoeneck, "Refining Search Terms for Nanotechnology," *Journal of Nanoparticle Research*, 10 (5): 715–728. Priority applications are patent documents in PATSTAT that report priority sequence of "1."

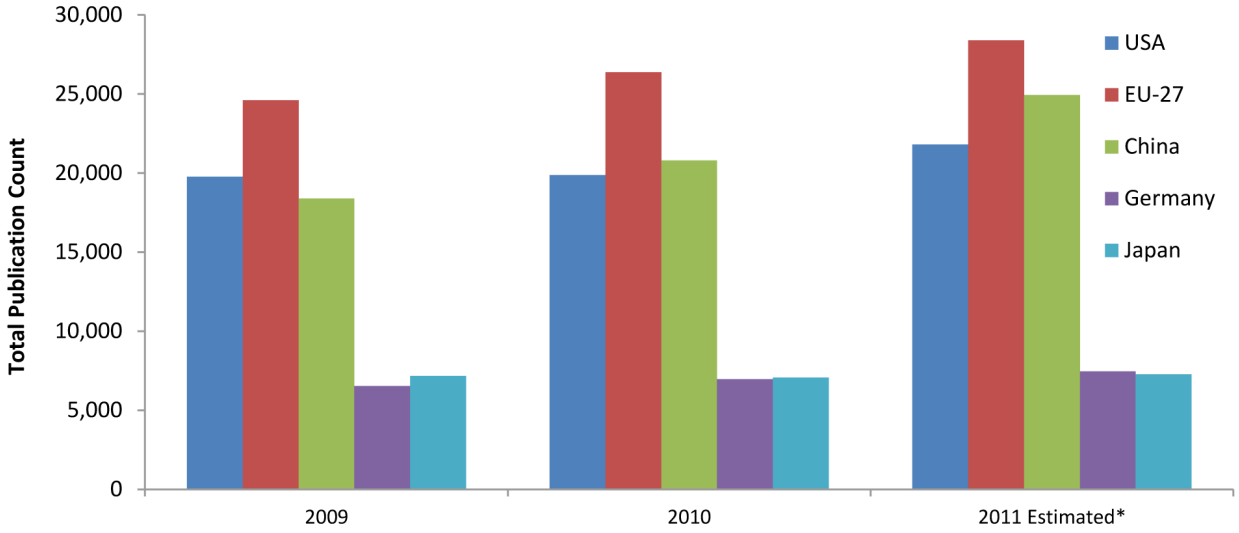
Source: Reproduced from President's Council of Advisors on Science and Technology (PCAST) 2012 Report, p. 7.

Yet, Germany has the largest nanotechnology market in Europe with nearly 400 companies involved with the development, production, or use of nanomaterials, including chemical and manufacturing firms.[118] According to the Federal Ministry of Education and Research, nearly half of all EU nanotechnology firms are based in Germany.[119] Germany is also a leader in nanotechnology research filing over 3,730 nanotechnology patents between 2000 and 2010, more than any other country in Europe and almost as great as the number of patents filed by the rest of the EU member states combined. This sheer volume of nanotechnology patents also makes Germany the top patent-producing country per capita in Europe (see Figures 2, p. 36 and 3, p. 36). Germany has also led in academic research producing 6,449 nanotechnology related publications between 1998 and 2009 an average of 7.86 publications per 100,000 residents (see Figure 4, p. 38). This empirical evidence suggests a burgeoning nanotechnology sector in Germany that is one of the most robust and innovative in Europe. To put this into perspective, Germany produced nearly 2.5 times the number of publications and almost 4 times the number of patents as the United Kingdom, the second largest market for nanotechnology R&D in the EU.[120]

Despite Germany's reluctance to allocate defense budget resources toward the development of nanotechnologies, the federal government is one of the largest sources of funding for nanotechnology R&D within the economy. In fact, Germany has the highest public sector investment in nanotechnology of any EU member state with its spending second only to the European Commission (ObservatoryNANO 2011). Public funding of nanotechnology R&D is estimated to be around €500 million ($US 676 million) per year with public investment increasing annually between 5-10%. Whereas in other countries, such as the United Kingdom, there is a greater proportional investment in nano R&D by the private sector, notably through venture capital investments, in Germany the state has taken a prominent role in strengthening nanotechnology as an economic sector. German industry, however, is third in the world in terms of its nanotechnology investments (see Figures 5 and 6, p. 66).

[118] ObservatoryNANO, " European Nanotechnology Landscape Report" (2011)
[119] ObservatoryNANO, " European Nanotechnology Landscape Report" (2011)
[120] ObservatoryNANO, " European Nanotechnology Landscape Report" (2011)

Figure 4. Publication counts for nanotechnology



Source: L. Kay, P. Shapira, J. Youtie, and A. L. Porter, Program on Nanotechnology Research and Innovation System Assessment Georgia Institute of Technology, Atlanta, Georgia, with support from the National Science Foundation (NSF) through the Center for Nanotechnology in Society (Arizona State University; Award No. 0937591) [Data as of January 2012].

Note: Search based on S. Arora, A. L. Porter, Y. Youtie, and S. Shapira, Capturing new developments in nanotechnology scientific output: A search strategy for publication records. STIP White Paper, Atlanta, Georgia, 2011.

*Annualized publication counts based on number of country-level publications identified as of 22 August 2011. Additional 5% added to account for publications expected to be released in the next calendar year (i.e., in early 2012).

Source: Reproduced from President's Council of Advisors on Science and Technology (PCAST) 2012 Report, p. 5.

The *High-Tech Strategy 2020 for Germany* released by the Federal Ministry of Education and Research emphasizes nanotechnology as one of the key sectors for future economic growth.[121] Strikingly, the report also discusses the desire for Germany to become a market leader in security technology products and services, including in the fields of biological, chemical, and nano technologies. In other words, while the federal government has been reluctant to invest in nanotechnology from a military and security perspective, the state has been actively involved in the development of nano-related industries even within the security sector to promote economic growth. The government's position on nanotechnology for security purposes therefore has focused less on relative hard power and military strength, than on commercial incentives within an increasingly integrated Europe and globalized world.

[121] BMBF, " Nano-Initiative: Action Plan 2010" (2007)

United Kingdom

In the United Kingdom, as for most European countries, security and defense concerns have become more global, extending beyond the boundaries of the state and requiring international cooperation and agreement. National governments in this context no longer exercise sole authority over security matters, but coordinate with other states through international organizations at the European and global levels. As has been the case throughout Europe, the United Kingdom has greatly reduced its defense spending over the past 30 years.[122] However, despite a clear decline in military spending, the United Kingdom remains the biggest defense spender in the EU and has been one of only two European countries, along with Greece, that has met NATO's minimal goal of at least 2 percent of GDP spending on defense.[123] While there has been a reduced role of the state overall in international security decision-making and an increased competency at the European and international levels, the defense policy position of the United Kingdom differs significantly from Germany. In particular, where German security seems intrinsically linked to European security and its domestic objectives are primarily pursued through multilateral means, the U.K. government has sought to retain its capacity to act independently whenever its national interest are at stake. Though committed to its international partners, the United Kingdom has sought separate bilateral agreements with the both the United States and France and has even undertaken unilateral troop deployments in recent years, an action that would not be a viable option in Germany.[124]

In contrast to German foreign and security policy ambitions, which are modest despite its large economic size and influence in the EU, the United Kingdom has a strong sense of responsibility for international security policy even though globally it can be categorized as a medium-ranking economic and military power. In many regards, this willingness to become directly involved diplomatically, economically and militarily has been shaped by the United Kingdom's history as a world power and its continued position as a permanent member of the United Nations Security Council. This position of continued involvement in international security issues has been identified in the 2010 UK National Security Strategy. Passages such as, "Britain's national interest requires us

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[122] Frédéric Mérand, *European Defence Policy: Beyond the Nation State* (Oxford University Press, 2008)
[123] CSIS, "European Defense Trends 2012: Budgets, Regulatory Frameworks, and the Industrial Base," edited by D. Berteau, G. Ben-Ari, R. Crotty, J. Hofbauer, P. Hermann and S. Raghavan, (2012)
[124] P. Cornish, *Strategic Cultures in Europe: Security and Defence Policies Across the Continent*, edited by H. Biehl, B. Giegerich and A. Jonas (Springer, 2013)

to reject any notion of the shrinkage of our influence" make clear the desire of the British state to maintain an active role in world security affairs.[125] Public opinion has also supported a more independent role of the United Kingdom and remained somewhat skeptical of an overall EU Common Defense and Security Policy. In addition to differences in historical experience and public perceptions about state involvement in international security affairs, compared to the German federal system, the UK government is less constrained by separation of powers. Policymaking takes place primarily at the national level with the Prime Minister exercising a great deal of influence.[126] As a result, the governing party has significant ability to pursue its own foreign and security policy agendas.

Reflecting this more active role of the state in security policy, the United Kingdom does not share the same proscriptions against funding nanotechnology R&D for defense purposes as Germany. In absolute terms, the United Kingdom is the largest spender on defense R&D within Europe spending nearly €4.3 billion ($US 5.8 billion) in 2001. However, corresponding with overall defense spending cuts, the amount of funds dedicated to defense-related R&D has decreased by more than half to €1.9 billion ($US 2.57 billion) by 2011.[127] The UK Ministry of Defense (MOD) allocates approximately £1.5 million ($US 2.4 million) per annum for the development of nanotechnology for security.[128] It is important to note however, that nano-related expenditures account for only 0.35% of the annual national scientific research defense budget and that the MOD considers the development of nanotechnology in the United Kingdom to be driven mainly by commercial incentives, rather than military imperatives. In other words, although the United Kingdom and Germany hold different perspective about the role of the state in security matters and have divergent defense policy positions, nanotechnology R&D in both countries is primarily pursued for economic gains rather than security needs.

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[125] P. Cornish, *Strategic Cultures in Europe: Security and Defence Policies Across the Continent*, edited by H. Biehl, B. Giegerich and A. Jonas (Springer, 2013)

[126] Kate O'Neill, *Waste trading among rich nations : building a new theory of environmental regulation* (Cambridge, Mass.: Cambridge, Mass. : MIT Press 2000a); Vivien A. Schmidt, "Procedural democracy in the EU: the Europeanization of national and sectoral policy-making processes." *Journal of European Public Policy* 13 (5):670-691 (2006)

[127] CSIS, "European Defense Trends 2012: Budgets, Regulatory Frameworks, and the Industrial Base," edited by D. Berteau, G. Ben-Ari, R. Crotty, J. Hofbauer, P. Hermann and S. Raghavan, (2012)

[128] NATO, " Committee Reports Annual Session 179 STCMT 05 E - The Security Implications of Nanotechnology" (2005)

Second only to Germany, the United Kingdom has one of the largest nanotechnology markets in Europe with nearly 250 firms involved with the development and production of nanomaterials and chemicals.[129] The United Kingdom is a leader in science and technology research and is one of the top publication-producing countries in Europe with 2,688 articles published between 1998 and 2009. The United Kingdom is also a leader in nano-related patents with 942 patents filed between 2000 and 2010 (See Figures 2 and 3, p. 36).[130] This makes the United Kingdom one of the most highly advanced markets for nanotechnology R&D within the EU. As has been the case in Germany, nanotechnology R&D has received considerable support and funding from the national government through public institutions including the Higher Education Funding Council for England and the Biotechnology and Biological Sciences Research Council. In addition to public funding, private investment has played an important role in the United Kingdom advancing nanotechnology research and providing capital for small business enterprises producing nanotechnology related goods and services.

While it is difficult to assess the amount of private investment in nanotechnology R&D, there are indications that the UK market has more diversified sources of funding than Germany, which relies primarily on public support for research and production. Corporate funding and venture capital are the two primary sources of private investments in nanotechnology R&D. While levels of investment for corporations may be similar in both countries, the United Kingdom has a more developed venture capital market capable of making investments in R&D. In 2002, venture capital investments in the United Kingdom were estimated to be €2.54 billion ($US 3.46 billion) compared with €1.34 billion ($US 1.83 billion) of investment in Germany (see Figure 6, p. 66).[131] This kind of investment is particularly valuable at the early start-up and expansion stages helping to fund research activities, product development, and marketing and frequently provides equity capital and managerial skills for new companies in high-tech and knowledge intensive sectors. This variation in funding opportunities for nanotechnology R&D is important, because even though both Germany and the United Kingdom are motivated by the potential economic gains of this emerging technology, their respective economic structures offer different opportunities for nanotechnology development.

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[129] ObservatoryNANO, " European Nanotechnology Landscape Report" (2011)
[130] ObservatoryNANO, " European Nanotechnology Landscape Report" (2011)
[131] European Commission, "Towards a European Strategy for Nanotechnology; Communication from the Commission," Brussels, Belgium: Commission of the European Communities (2004)

CHINA

When compared to both Germany and the United Kingdom, China exhibits a top-down approach to nanotech R&D. China, as the following indicates, prioritizes those technologies, such as nanotech, that are seen to have significant strategic value. Even so, China appears to view nanotechnology primarily as a means to improve its position economically, pursuing commercial nanotechnology applications over military ones.[132] This section offers two mini-case studies of China's approach to nanotechnology. Roselyn Hsueh provides the necessary background on economic reform in China in order to understand the relationship between strategic technological development and the Chinese leadership's understanding of national security and strategic value. She illustrates this relationship with regard to nanotech-enabled textiles, of which China is a leading producer. Margaret E. Kosal then paints a detailed picture of China's approach to nanotechnology policy and R&D. Together, these mini-cases provide the broader domestic political and economic context for the assessment of China's perception of nanotechnology as a primarily commercial area for development and to give insight into how China will govern commercialization of nanotech-enabled products.

China: The Domestic Political Economy of National Security and Nano-textiles

By Roselyn Hsueh

For reform-era China, technological advancement and infrastructural development cannot be disconnected from the state's concerns for national security. Security imperatives, in the post-Mao and the post–cold war eras, have been maintenance of political regime stability and, relatedly, China's status as the only major "Communist" power in the world with a regional security system positioned against it. The Chinese leadership perceives the end of the cold war as the dawn of American military leadership in East Asia, targeting regional security against China and exerting ideological, if not also political, supremacy elsewhere. Chinese President Xi Jinping's "Chinese dream" added civility and environmental protection to the quest for economic power and social and political stability as regime goals. In other words, what is considered strategic economically to the Chinese government involves security-related calculations that are both internally oriented and

[132] Anne L. Clunan, personal communication with senior member of the NSET subcommittee, Washington, DC, May 31, 2013.

geopolitical in nature.[133] The bottom line is that Chinese leadership perceives that it must identify and manage political, economic, and social forces that might derail external and internal regime stability and China's growth and development.

Government officials, leaders of commercial sectoral and business associations, and managers of state- and privately owned enterprises stress the connection between acquiring national technological competence and "making China rich and strong" in the face of unnamed threats.[134] Since the 1980s, the Chinese state introduced market competition on the aggregate level but retained centralized control of industries considered strategic to national security (including geopolitics and political stability) and with a high contribution to the national technology base.[135] Motivated by national security concerns and the development of technological capacity, the Chinese state perceives as strategic those industries that have applications for maintaining political stability and contribute to the national technology base and economic competitiveness. Informants identify security considerations and "royalties, profits, and relative economic gains" as drivers of deliberate

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[133] Christensen and Segal discuss the overlap between external and internal security concerns: Clayton Christensen, *The innovator's dilemma : when new technologies cause great firms to fail* (Boston Mass.: Harvard Business School Press, 1997); Clayton Christensen, "The Ongoing Process of Building a Theory of Disruption.(Dialogue on the Effects of Disruptive Technology on Firms and Industries)," *Journal of Product Innovation Management* 23 (1):39 (2006); S. Anand, P. Segal, and J. Stiglitz, *Debates on the measurement of global poverty*, *The Initiative for Policy Dialogue series* (Oxford ; New York: Oxford University Press, 2010). Shambaugh contends that "domestic stability" is always paramount and that external threats are usually perceived in the context of aggravating domestic instability D. Shambaugh, *Modernizing China's military progress, problems, and prospects* (Berkeley, CA: University of California Press, 2002).

[134] Personal communication in Beijing in September 2008 with a government official at the Research Development Center of the National Development and Reform Commission.

[135] This research on China is based on in-depth, semi-structured interviews conducted in the eastern coastal and western interior provinces between 2005 and 2008 and in 2011 with former and current bureaucrats and officials of central and provincial level government offices; managers and executives of state-owned carriers and domestic and foreign-invested service providers and equipment makers; and officials of sector and business associations and foreign delegations. Primary documents and secondary research supplemented the fieldwork.

state control.[136] One informant characterizes the relationship between technological goals and security imperatives as "the government's obsession with economic security."[137]

The Chinese state connects external and internal security concerns with goals of advancing and controlling China's technology infrastructure, disseminating information, and managing labor markets. Various five-year and fifteen-year plans and catalogues for guidance of foreign investment, released by the National Development and Reform Commission, have named infrastructural and high technology sectors as areas for modernization, which require "absorbing and digesting" FDI and foreign technology, and indigenous development. They have also have emphasized domestic consumption in addition to export-orientation.[138] Funding programs, such as the 1986 National High Technology Development Program (863), which includes nanotechnology, have jumpstarted basic-science-to-commercialization initiatives. More recently, the guiding opinion issued by the State Council in 2006, identified the keys sectors critical for national security and the survival and competitiveness of the economy: military production, electricity (grid and power generation), petroleum, telecommunications, coal, civil aviation, and shipping.[139]

Nano-enabled industrial and technical textiles

China is a leading producer of industrial and technical textiles and clothing, which contain nanotech-enabled components.[140] The industrial and technical textile subsectors are economically and militarily salient, unlike regular textiles, as they contribute to the Chinese national technology base and have applications for construction, aerospace (including air transport and space exploration), and significant military uses (as outlined in the above section on "What Is Nanotechnology?"). Tianjin Polytechnic University's Institute for Composite Materials, which produced material for the Shenzhen spacecraft, receives funding for basic research in nanoscale carbon fiber, e.g., high

[136] Quote from Suttmeier 2005, 35-37. Suttmeier, Yao, and Tan 2006 examine the relationship between technical standards-setting, economic goals, and security concerns.
[137] Interview in Beijing on September 23, 2008, with a former Beijing University of Posts and Telecommunication professor, who directs a Ministry of Science and Technology research center.
[138] Quote from interview in Beijing on September 19, 2006, with the government relations director of a foreign-invested networking equipment maker.
[139] See State Council's "The Guiding Opinion on Promoting the Adjustment of State-owned Capital and Reorganization of State-owned Enterprises," released on September 16, 2006.
[140] See Margaret E. Kosal contribution to this report, p. 34. See also R. Parker and R. Appelbaum, *Can emerging technologies make a difference in development?* Edited by Rachel A. Parker and Richard P. Appelbaum (New York: New York : Routledge, 2012)

performance fiber for military and national security applications. High performance nanotechnology-enabled fiber as key inputs for air, oil, and gasoline filters—with their environmental implications—are of particular interest to national-level bureaucracies targeting funding for basic research and commercialization.[141]

Photo: Astronauts of the Shenzhou VII, the third in China's space program, wore suits containing advanced synthetic fabric developed by Chinese scientists.

Source: Xinhua, 2008; http://news.xinhuanet.com/newscenter/2008-09/25/content_10108562.htm.

In these subsectors, relevant central-level Chinese bureaucracies collaborate with sector associations to distribute limited central funding for R&D and set technical standards to strengthen domestic

[141] Interview on March 11, 2013, in Shanghai, with Wang Yimin, professor of chemical engineering, Donghua University.

capacity in man-made fabrics and geosynthetics.[142] In addition to the various five-year plans specifically naming technical textile sectors as areas of strategic focus (and investment catalogues discouraging or forbidding high-polluting sectors), central-level research funding in the 2000s, while limited, has focused on technical and industrial transformation and innovation in these subsectors.[143] "Commercialization," however, "is at least five to ten years away in nanoparticle finish, i.e. stain resistant fabrics; and even then the nonsecurity market is small domestically and globally," according to Pan Ning, professor of Fiber and Polymer Science at U.C. Davis.[144]

Strategic Value Chinese Style, and the Political Origins of Nano-textile Regulation

The *strategic value of a sector* is a critical determinant of why and how reregulation of economic sectors occurs in China; and while that strategic value differs across industries, its determination occurs at the national level.[145] On the economic dimension, strategic value is defined by a sector's value input in the country's technological and infrastructural base and the contribution of a given sector to the competitiveness of other sectors and the rest of the economy. A sector's application for national security, including internal political and social stability, external security, and foreign relations, characterizes the political dimension of the objective definition of strategic value.[146] The scope and nature of Chinese market reregulation is shaped by its implications for the political survival of the most important decisionmakers, not economic calculations alone. On these objective political and economic measures, the nanotechnology-enabled nonwoven fibers and technical textiles subsector scores as medium to high in security salience and low to medium in economic salience. The relative degree of strategic value has implications for the type of market coordination and level of state intervention across capital- and labor-intensive subsectors within textiles.

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[142] Interviews in April, May, and September 2006 in Jiangsu and Zhejiang provinces and greater Shanghai with managers of Polyfelt and Performance Fiber and Ocean Power, foreign-invested and domestic private technical textile manufacturers, respectively.
[143] Interview on March 12, 2013, in Beijing, with Li Lingsheng, chairman of China Nonwovens & Industrial Textiles Association.
[144] Interview on October 14, 2013 in Davis, California.
[145] This conceptualization of the *strategic value of a sector* builds on Roselyn Hsueh, "China and India in the Age of Globalization: Sectoral Variation in Postliberalization Reregulation." *Comparative Political Studies* 45 (1):32-61 (2012), and Roselyn Hsueh, *China's regulatory state : a new strategy for globalization*, *Cornell studies in political economy* (Ithaca: Cornell University Press, 2011).
[146] Kiren Aziz Chaudhry, *The price of wealth : economies and institutions in the Middle East*, *Cornell studies in political economy* (Ithaca: Cornell University Press, 1997).

Generally speaking, China reflects openness toward foreign and private entry in labor-intensive subsectors and a more deliberate approach in capital-intensive subsectors to maximize gains in areas with application for national security and contribution to the national technology base. It relinquishes control of what it perceives as nonstrategic industries and enhances its control of those industries considered strategic because of their contribution to national security and the national technology base. The state's capacity to implement this strategy resides in the Chinese Communist Party's monopoly over personnel management and the devolution of economic power in the nonstrategic areas.

How the Chinese leadership defines strategic value, however, does not always fall neatly within the boundaries of objective measures. Boundaries between the economic and political dimensions blur in practice due to the subjectivity with which political leaders and policymakers bring to defining, making claims about, and contesting, the strategic value of a sector. The case of China's textile industries show that analysis of the *subjective* assessment of "objective" measures of strategic value provides critical information about the goals and means of the Chinese state in market governance. Taking account of the subjectivity inherent in defining strategic value provides better understanding of how the Chinese rank order and create scores on objective measures.

Based on overall objective measures of national security and technological development, nanotech-enabled and other technical textiles should be deemed strategic to the Chinese state. In such technologically advanced sectors, the state would not be expected to easily introduce market competition before considering security implications and would be expected to exercise intervention in ways that would contribute to the development of potential applications in military, aerospace, and other related areas. Industrial and technical textiles have a high-technology content; some product categories are inputs for construction, space, and aviation sectors, which have military applications. Compared to capital-intensive industries, such as telecommunications, the textile industry falls on the low end of the technological ladder, but because of potential military and aeronautical applications, the strategic value logic expects relevant central ministries to intervene to promote industrial upgrading and FDI in high-tech, high-value-added subsectors. Central and local governments would also introduce fiscal and other subsidies to promote the development of high-tech textile equipment and fabrics, which are sometimes unavailable as imports because of other countries' export restrictions.

Prior to the 1980s, the Chinese government had governed textiles with more bureaucratic centralization than it had governed telecommunications. Deliberate state actions beginning in the Deng era, however, have recalibrated market coordination and the distribution of property rights to maximize the economic benefits and minimize the political costs of more markets and private interests in the political economy. Less concerned about controlling products or services that have few applications for national security and low contribution to the national technology base, the Chinese government introduced competition in the textile industry in the 1980s and decentralized market coordination to local governments and commerce bureaus by the early 1990s.

The overall low strategic value of textiles and the path-dependent effects of textile's decentralized market governance limit the actual type and amount of central resources devoted to textile sectors and issues.[147] The dismantling of the Ministry of Textile Industry in 1993 officially relinquished central coordination in textiles. The downgrading of the Ministry of Internal Trade, which dominated the distribution of raw and processed textile materials in 1998, further decentralized supervision of the industry, as did the corporatization and restructuring of state-owned trading companies. Even as market reforms reinforced centralized coordination in telecommunications, the demoted textile offices operated as bureau-level departments with little authority. These institutional developments set the stage for private sector development and a local-stakeholders-initiated surge in FDI. The Chinese state exercises limited sector-specific coordination mechanisms, relying mainly on macroeconomic instruments to guide the industry.

The Chinese case of the textile industry demonstrates that, conforming to the subjective understanding of the relative unimportance of textiles, the Chinese government has not significantly reregulated the textiles industry, including the nanotech-enabled industrial and technical textiles subsectors. The Chinese central state exercises decentralized engagement in textiles, including nanotechnology-enabled ones; it has relinquished state control in industrial developments, decentralizing market regulation to local bureaucracies and market actors and introduced competition and privatized nearly all market segments and subsectors. However, conforming to the objective measures of strategic value, in technical textile segments, which have heavy reliance on nanotechnology-enabled components and significant R&D inputs, Chinese central government

[147] Interviews in 2006 and 2013 with technical textile producers and staff representatives of textile sector and business associations in Beijing, Jiangsu, Shanghai, Shenzhen, and Zhejiang.

funding and limited coordination facilitate research at universities and S/T bureaucracies on specific categories critical for designated projects of national importance. These include "super suits" and other advanced composite materials involved in China's space program.

Despite the objective strategic value of nano-textiles and much national pride in the production of "super space suits" using indigenously produced nano-textiles, the Chinese government has not exercised significant regulatory control over this industrial sector. Nano-enabled textile applications in military and aerospace notwithstanding, the Chinese government has relinquished state control over market developments and extensively liberalized the textile industry, one of the earliest to experience deregulation and industrial development driven by nonstate market actors. The decentralization of economic decision making, unleashing of market reforms, and selective state intervention in value-added textile subsectors has created an agile and flexible export-oriented manufacturing base in China and developed domestic capacity in technical textiles. The long-term effects of the Chinese strategic-value regulatory strategy have created comparative advantages in industrial development. This strategy has allowed the Chinese government to deploy limited resources in sectors and issue areas that matter the most, thereby enhancing overall regulatory capacity. By insulating the central government from sectoral interests, the strategic-value strategy has also helped ensure the continued survival of China's authoritarian regime.

China's Institutions and Leadership Policy in Nanotechnology Development

By Margaret E. Kosal, PhD

The rapid development of nanotechnology in China is closely tied with the legacy of a centralized state planning system in science and technology development since the 1950s. The role of the P.R.C. central state is characterized as prioritizing areas of research that could increase the P.R.C.'s international status or political goals, and then amassing resources (human capital, funding, and administrative support) to achieve breakthroughs in these areas. With respect to nanotechnology, China is pioneering to set up a top-down system of steering and coordinating its development at the national level. [148] In the National Long- and Medium-Term Plan for Science and Technology

[148] M. Hu, "Nanotechnology development in Mainland China." IEEE Conference on Technology and Society in Asia (2012)

Development (2006-2020) enacted by the P.R.C. State Council, the "breakthroughs in the study of nanotechnology" is listed as one of the four important scientific research plans in basic research.[149]

China's nanotechnology development and state interest in prioritizing research in nanotechnology can be attributed to the influential research conducted by a few key Chinese scientists since the 1980s. Bai Chunli, now the president of the Chinese Academy of Sciences (CAS), is one such influential figure. Bai graduated from the PhD program of the Institute of Chemistry of CAS in 1985 and became a postdoctoral scholar at the California Institute of Technology working at the prestigious Jet Propulsion Laboratory (JPL). Bai returned to China in 1987 and started a research program using the STM (Scanning Tunneling Microscopy) at the CAS, and became one of the first scientists in China conducting nanoscale research.

Since the mid-1980s, the National Natural Science Foundation of China (NSFC) and the CAS have started supporting research on STM-related research, and gradually wider research topics at the nanoscale. [150] In 1986, the National High-Tech Research and Development Program (known as the 863 Program) was implemented by the then State Science and Technology Commission (SSTC), the predecessor of the current Ministry of Science and Technology (MOST), singling out research on the application of nanomaterials as one priority area in public funding. The 863 Program on the whole was implemented through successive Five-Year Plans, and from 1990 to 2002, the Program funded over one thousand nanotechnology projects with total funding support of $27 million. Specifically, in 1990, the SSTC initiated the 1990-99 10 Year "Climbing Up" Project on Nanomaterial Science to support research on nanomaterials, adhering to the goal of the 863 Program.

In 1997, Bai was promoted to be an alternate member of the Communist Party of China (CCP) Central Committee. In the same year, the SSTC enacted the National Basic Research and Development Program, known as the 973 Program, further concentrating support for the development of nanomaterials and nanostructures.[151] The 973 Program complemented the 863 Program in research investment, and enhanced the standardization of nanotechnology research.

[149] PRC, The State Council of the People's Republic of China (2006)
[150] Chinese Academy of Sciences, Institutional Repository of Institute of Mechanics (2013); China Daily, "China has become a global nanotechnology leader, says the CAS President Bai Chunli (in Chinese)," *China Daily* (2013).
[151] C. Bai, "Ascent of nanoscience in China," *Science Magazine* (2005)

Two notable projects under the 973 Program concerned the standardization for the key measurement techniques in nanotechnology (led by Professor Jiang Chao at the National Center for Nanoscience and Technology), and Controlled Synthesis of Nanometer-sized Reference Materials for Metrology and Measurement (led by Professor Wu Xiaochun at the National Center for Nanoscience and Technology).[152] In 1998, the CAS piloted its own Knowledge Innovation Program, which gave nanotechnology priority in high-tech development and technology transfer. The Program mapped out plans for the incubation of high-tech startup companies by institutions affiliated with the CAS.[153] In 2004, Bai himself was further promoted to be the executive vice-president of the CAS with full minister rank.

Besides the advocacy work by prominent research scientists like Professor Bai Chunli who have high status both within the science community and the central government, China's decision to prioritize nanotechnology development was also prompted by international exchange in nanotechnology research and global competition in government-support initiatives for nanotechnology development. As early as 1986, the CAS invited Gerd Binnig and Heinrich Rohrer, two pioneer scientists in nanotechnology research who received the Nobel prize for the design of the STM, to visit the CAS and exchange information with the CAS scientists.[154] Heinrich Rohrer reportedly wrote a letter in 1993 to then P.R.C. President Jiang Zemin predicting the emergence of nanotechnology in industrial development, saying that "future technology belongs to those countries which are wise to accept nanoscale as the new standard of technology, and pioneer its research development and use."[155]

In 2000, the United States officially launched the National Nanotechnology Initiative (NNI). According to interviews conducted by Appelbaum et al., the P.R.C. central government "did not fully embrace nanotechnology until countries such as the United States had formulated national nanotechnology initiatives, which made it easier for Bai and his colleagues to make their case to the

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[152] D. Jarvis and N. Richmond, "Regulation and Governance of Nanotechnology in China: Regulatory Challenges and Effectiveness," *European Journal of Law and Technology* 2 (3):1-11 (2011)
[153] Chinese Academy of Sciences, Institutional Repository of Insitute of Mechanics (2013)
[154] R. Leung, "Doing Nanotechnology in China," Doctor of Philosophy Degree in Sociology, Sociology Department, University of Wisconsin-Madison (2008)
[155] Caijing, "Nano is Coming, Finding the Right Path First (in Chinese)," *Caijing Magazine* (2013)

scientific and political leadership."[156] In the same year, the National Steering Committee of Nanoscience and Nanotechnology (NSCNN) was established to oversee national policies and coordinate funding for all R&D funding organizations in the country, with the head of MOST as the director and vice ministers of MOST, the vice president of the CAS, and vice president of the NSFC as the vice directors. Members of the NSCNN included government officials from the Ministry of Education, the National Development and Reform Commission (NDRC), the Chinese Academy of Engineering (CAE) and the Commission on Science, Technology and Industry for National Defense.

The following year, the P.R.C. President Jiang Zemin (also the General Secretary of the CCP Central Committee) remarked that, "the development of nanotechnology and new materials should be regarded as an important task of the development and innovation in science and technology. The development and application of nanomaterials and nanotechnology is of strategic significance to the development of high technology and national economy in China."[157] The NSCNN drafted the "Guojia Nami Keji Fazhan Gangyao" (National Nanotechnology Development Strategy) (2001-2010), the first of its kind in China resembling similar initiatives as the NNI in the United States.[158]

The National Nanotechnology Development Strategy was a blueprint for Chinese nanotechnology development for the 2001-2010 decade. It emphasized the importance of increasing government funding support for nanotechnology development, and prioritized commercialization of nanotechnology, training competent R&D personnel, appropriating intellectual property from R&D, and building up a national nanotechnology innovation system in the 10th Five-Year Plan (2001-2005). It called for technological breakthroughs in "nanomaterials production and fabrication, construction and integration of nanoscale devices, nanofabrication technologies, nano-scale structural analysis and performance testing techniques, and indigenous innovation in nanomaterials

[156] R. Appelbaum, Cao C., R. Parker, and Y. Motoyama, "Nanotechnology as Industrial Policy: China and the United States," Paper presented at the 2013 International Studies Association Annual Conference, San Francisco, CA (2013)
[157] Xinhua, "President Jiang Zemin Meets with Delegates of 2001 International Nanomaterials Conference (in Chinese)" (2001)
[158] MOST, "National Nanotechnology Development Strategy (in Chinese)," *MOST* (2001)

production devices."[159] In military technologies, it called for "the development of nanotechnology and other high energy fuel Pyrotechnics Technology, breakthrough in nanostructured materials and special purpose coatings technology, development of integrated applications of nanotechnology sensors, control and motion systems and integrated micro-electromechanical systems technology for the micro / nano-type aircraft, micro / nano-satellite systems and special purpose integrated technology platform."[160] The 10th Five-Year Plan also set goals for the short-term (development of nanomaterials), medium-term (development of bio-nanotechnology and nanomedical technology) and long-term (development of nano-electronics and nanochips).

More recent government policies have focused on leapfrogging the technology gap in key areas of research and building a system of innovation. MOST established the Nanotechnology Industrialization Base of China (NIBC) in Tianjin (a municipality not far from Beijing) in 2000, with support from the CAS to serve as the principal incubator for nanotechnology research spin-off companies. In 2005, MOST, CAS and the local Tianjin Municipality Government jointly established the China National Academy of Nanotechnology & Engineering (CNANE) within the same facility of NIBC, focusing on R&D development and fostering synergies between R&D and commercialization.

In the 11th Five-Year Plan (2006-2010) the central government placed further strong emphasis on innovation, including "industrializing the technology for 90-nanometer and smaller integrated circuits" and developing "new materials badly needed in information, biological and aerospace industries."[161]

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[159] MOST, "National Nanotechnology Development Strategy (in Chinese)," *MOST* (2001); Guojia Nami Keji Fazhan Gangyao" (National Nanotechnology Development Strategy) (2001-2010), translation from the original Chinese document.
[160] MOST, "National Nanotechnology Development Strategy (in Chinese)," *MOST* (2001), Guojia Nami Keji Fazhan Gangyao" (National Nanotechnology Development Strategy) (2001-2010), translation from the original Chinese document.
[161] Y. Zheng and M. Chen, "China plans to build an innovative state" (Nottingham, UK: China Policy Institute, 2006)

Current state of China's nanotechnology development

China has emerged as the one of the global leaders in development of nanotechnology. China has ranked only second to the U.S. in nanotechnology investment.[162] China has ranked second in the number of peer-reviewed research publications relating to nanotechnology until 2013 (only behind the United States which produces about 70% more publications than China (see Figure 4, p. 38) and the second in the number of patents related to nanotechnology since 1998 (see Figures 2 and 3, p. 36).[163] China has also become a leader in the production of some nano-related industrial products, for instance, as Roselyn Hsueh notes above, the nano filters for air conditioners, nano-material textiles and clothing that have enhanced antimicrobial properties, the nano coatings and plastics for refrigerators, and anti-corrosive nano paints used in oil tanks.[164] Although China still lags behind the United States and leading European countries in measures of research quality (i.e., ratio of high-impact journal publications) and in terms of commercialization of research (i.e., share of nanotechnology patents held by industry),[165] it is determined to catch up and leapfrog the development cycle.

China has also actively engaged in integrating its nanotechnology research and development with the global market and R&D platform, through developing international and national standards on nanotechnology. The National Center for Nanoscience and Technology led a project on researching nanotechnology standards for the 11th Five-Year Plan, which set the goal of creating international and national technology standards to ensure China's place in the "intense competition between global measurement and research organizations," because of the important role that standards play

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[162] Philip Shapira and Jue Wang, "From Lab to Market? Strategies and Issues in the Commercialization of Nanotechnology in China," *Asian Businesses and Environment* 8 (4):461-489 (2009)

[163] China Daily, "China has become a global nanotechnology leader, says the CAS President Bai Chunli (in Chinese)," *China Daily* (2013)

[164] R. Appelbaum et al., "Nanotechnology as Industrial Policy: China and the United States." Paper presented at the 2013 International Studies Association Annual Conference, San Francisco, CA (2013); R. Parker and R. Appelbaum, *Can emerging technologies make a difference in development?* Edited by Rachel A. Parker and Richard P. Appelbaum (New York: New York : Routledge, 2012)

[165] Jan Youtie, Philip Shapira, and Alan L. Porter, "Nanotechnology publications and citations by leading countries and blocs.(Report)," *Journal of Nanoparticle Research: An Interdisciplinary Forum for Nanoscale Science and Technology* 10 (6):981 (2008).

in high-tech industry development. By 2011 (the end of the 11th Five-Year Plan), China has developed six international nanotechnology standards, and has implemented 22 national standards.[166]

Nanotechnology industry stakeholders in China

Government

The longitudinal analysis of China's nanotechnology development above has already highlighted the role of central government intervention in nanotechnology development in China. It should be noted that apart from the various initiatives and programs from the political actors at the central government (MOST, NSFC, CAS, CAE, etc.), local governments also play a crucial role in the creation of a national innovation system integrating research in the upstream and manufacturing in the downstream. Local governments provide support for local nanotechnology development programs. Most notable among these are the Dengshan (Climbing Up) Action Plan enacted by the Shanghai Municipality Government and dedicating funds to nanotechnology research, and the Shanghai Nanotechnology Promotion Center (SNPC), which provides funding and coordinates research in nanotechnology across seven local universities and nine private firms. Local governments are able to provide infrastructure support, business development support, and preferential packages in taxation and financing to high-tech entrepreneurs and foreign enterprises.

Universities and state-sponsored research institutes

There are hundreds of universities and state-sponsored research institutes actively engaged in nanotechnology research in China, with the most prominent universities and institutes concentrated in Beijing and Shanghai. In 2003, Tsinghua University, Peking University, and the CAS jointly established the National Center for Nanoscience and Nanotechnology (NCNST) in Beijing, with additional support from MOST, NDRC and the Ministry of Education (MOE). Bai Chunli serves as the director of NCNST. NCNST is involved in research in four areas: nanoprocessing and nanodevices, nanomaterials and nanostructures, nanomedicine and nanobiotechnology, nanostructure characterization and testing.[167]

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[166] National Center for Nanoscience and Technology, "Nanotechnology Standard Research result Presented at the 11th Five-Year Plan National Prominent S&T Achievement Exhibition (in Chinese)," National Center for Nanoscience and Technology (2011)
[167] NCNST, "Official website of the NCNST (in Chinese)" (2013)

Also in 2003, the Shanghai National Engineering Research Center for Nanotechnology (NERCN) was established by the National Development and Research Commission (NDRC) in Shanghai, whose major shareholders included the local CAS institutes, Shanghai Jiaotong University, Fudan University, East China Normal University, several local firms and SNPC. It focuses on nanotechnology R&D in areas including environmental protection, renewable energy, information technology, biomedical engineering and new materials.[168]

Companies

The number of Chinese nanotechnology firms is estimated at around 800-1000; however, information about them is scarce.[169] There is not a national industry association for nanotechnology, and government bureaus do not track the number of firms. Most of the nanotechnology companies are concentrated in Beijing, Tianjin (which hosts the NIBC), Shanghai (which hosts SNPC), Suzhou (a city in Zhejiang Province which has the SIP BioBay, China's first international innovation park focusing on nanotechnology and biotechnology within the Suzhou Industrial Park) and Guangdong Province. Over 80% of the nanotechnology firms collaborate with universities or research institutes either in China or abroad.[170] Nanotechnology firms are permitted to apply for certification as a "high-tech firm" in order to apply for grants from national high-tech programs. For a company to be certified as such, it must meet certain requirements set forth by the relevant government bureau, such as intellectual property ownership, minimum percentage of employees with higher education degrees, and minimum percentage of revenues devoted to R&D.

The commercialization of nanotechnology in China has been slow compared to advanced countries such as the United States. The Medium- and Long-Term Plan for the Development of Science and Technology (2006-2020) (MLP) listed nanotechnology under the basic science program section rather than the engineering section. According to Appelbaum et al., most nano-products produced by Chinese firms are low-level technology, and the eventual inclusion of nanotechnology in the MLP represents the central leadership's trust of nanoscientists like Bai Chunli, who emphasize

[168] NERCN, "Official website of the NERCN (in Chinese)"(2013).
[169] Italian Trade Commission Shanghai Office, "Market Report on China Biotechnology and Nanotechnology Industries" (2009)
[170] Italian Trade Commission Shanghai Office, "Market Report on China Biotechnology and Nanotechnology Industries" (2009)

nanotechnology's extraordinary potential for trillions of dollars in commercialization revenue in the future (if indeed they materialize at all).[171]

Technical alliances

An emerging type of stakeholder in China's nanotechnology development is the technical alliance that aims to solve critical technological problems by leveraging the capabilities and resources of both industry and research institutions within a certain area. For instance, in 2010 the CAS Institute of Solid State Physics established in Anhui Province the Anhui Nanomaterials and Application Technology Innovation Strategic Alliance, which involves more than 20 research institutes and universities and firms in the province. These kinds of loose alliances are nascent and their impact is hard to predict at this point.

Media and the public

The science reporters in China are generally positive towards the development of nanotechnology. According to a study conducted by the CAS on reporting on nanotechnology from two leading newspaper agencies, *Science Times* and *Science and Technology Daily,* from 2000 to June 2009, the number of reports on the negative aspects of nanotechnology accounted for only 11% of the total reports.[172] The media reports on the negative influence of nanotechnology center on basic research results, rather than the wider social and ethical issues that may arise due to nanotechnology development.

Although the general public in China is largely excluded from science policy decision-making processes, the public perception of nanotechnology has been predominantly positive and correlated with the public veneration for state-sponsored high-tech industries to which the central leadership has credited the "rise of China." The word "nano" has become a fashion in advertising new products to the public. A quick search on advertisements in Chinese online stores yields such popular products as "nano energy cups," "nano advertising umbrellas," and "nano magnetic pants," which target public admiration of "nanotechnology" and the lack of strict regulation on advertising

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[171] R. Appelbaum et al., "Nanotechnology as Industrial Policy: China and the United States." Paper presented at the 2013 International Studies Association Annual Conference, San Francisco, CA (2013); R. Parker and R. Appelbaum, *Can emerging technologies make a difference in development?* Edited by Rachel A. Parker and Richard P. Appelbaum (New York: New York : Routledge, 2012)

[172] C. Fan and L. Li, "Research on coverage of domestic mainstream media on new and emerging technology: in the case of GMO and Nanotechnology (in Chinese)," 5th Chinese Science and Technology Policy and Management Annual Conference (2009)

that exaggerates product functions. The head of the NSCNN observed that "nanotechnology is highly technical, requires specialist knowledge, and the public doesn't have the technical capacities or knowledge to understand the technologies or assess potential risks."[173] NCNST has hosted two science education programs for the general public, including science lectures, exhibitions, and visits to the labs. However, these preliminary activities in education and outreach on the science of nanotechnology are far from enough to make the general public sufficiently informed.

Ethical, legal, and safety concerns on nanotechnology development in China

As of 2011, there were more than 30 research organizations in China conducting research on the toxicological and environmental effects of nanomaterials and nanoparticles, and the techniques to recover nanoparticles from manufacturing.[174] The most notable one is the Joint Lab for Biological Effect for Nanomaterials and Nanosafety established by the Institute of High Energy Physics of the CAS and the NCNST in 2006. Bai Chunli, the chief architect of China's nanotechnology development said at the lab establishment ceremony that "we cannot follow the old path of treatment after pollution…now as we start developing nanotechnology we should also study nanosafety, so that nanotechnology can become the first mature high technology safe and beneficial to human beings with negative influences already seriously studied and carefully considered beforehand."[175]

In 2009, researchers at the Department of Occupational Medicine at Beijing Chaoyang Hospital published one of the first studies in the world linking nanoparticles to toxic damage of organs of human workers exposed to them.[176] Previous animal studies and *in vitro* experiments showed that nanoparticles can result in lung damage and other toxicity, but until this study there had not been reports on clinical toxicity in humans due to nanoparticles.

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[173] D. Jarvis and N. Richmond, "Regulation and Governance of Nanotechnology in China: Regulatory Challenges and Effectiveness," *European Journal of Law and Technology* 2 (3):1-11 (2011)
[174] D. Jarvis and N. Richmond, "Regulation and Governance of Nanotechnology in China: Regulatory Challenges and Effectiveness," *European Journal of Law and Technology* 2 (3):1-11 (2011)
[175] Science Daily, "Joint Lab for Biological Effect for Nanomaterials and Nanosafety is established (in Chinese)." *Science Daily* (2006)
[176] Y. Song, X. Li, and X. Du, "Exposure to nanoparticles is related to pleural effusion, pulmonary fibrosis and granuloma," *European Respiratory Journal* 34 (3):559-567 (2009)

Apart from safety concerns with nanotechnology, there have also been rising concerns among Chinese academics on the social consequences of nanotechnology development, for instance the potential misuse of nanotechnology by terrorists, the lack of equity in access to nanomedicine between the rich and the poor, and the potential long-term damage of nanomaterials to the ecological environment. *China Social Science Today*, the flagship journal of the Chinese Academy of Social Sciences, published a special issue in 2010 entitled "Interdisciplinary View of Nano-ethics" (Issue 125), which contained viewpoints from leading nanotechnology research scientists and social scientists. The experts suggest that research on ethical, legal and social issues of nanotechnology development should be strengthened, and given the highly interdisciplinary nature of nanotechnology, there needs to be further dialogue between the science community and the social science community, greater public awareness of ethical issues related to nanotechnology, and established channels for the general public to participate in ethical and policy-related discussions.

As the preceding demonstrates, developing, emerging, and advanced countries are busily promoting nanotechnology via national industrial strategies, despite uncertainty over its military and economic potential, societal, environmental and health consequences, and commercial appeal. China hopes that nanotechnology will allow it to leapfrog to the top of the international technological hierarchy. The next section considers whether nanotechnology is likely to up end the existing hierarchy of technologically advanced countries and the structure of global power relationships.

V. Technological Innovation and Leadership in a Globalized World

Science and technology play a dual role in establishing global power hierarchies; they are widely seen as the keys to economic growth and military dominance—the material base for national wealth, power and increased international status.[177] Technological revolutions have altered the balance of

[177] Michael Barnett and Martha Finnemore, *Rules for the World: International Organizations in Global Politics* (Ithaca, NY: Cornell University Press, 2004); Robert Gilpin, *War and change in world politics* (Cambridge, MA: Cambridge University Press 1981); Immanuel M. Wallerstein, *The modern world-system* (New York: New York : Academic Press, 1974); John W. Meyer and Brian Rowan, "Institutionalized Organizations: Formal Structures as Myth and Ceremony," *American Journal of Sociology* 83 (2):340-363 (1977); John W. Meyer et al., "World Society and the Nation-State," *American Journal of Sociology* 103 (1):144-181 (1997); Martha Finnemore, *National Interests in International Society* (Ithaca, NY: Cornell University Press, 1996). On the self-reinforcing nature of hierarchy, see Joe C.

economic, military, and political power throughout the course of history, and policymakers are consequently keenly interested in maintaining national advantages in S/T innovation and seizing the lead in any emerging technological revolution.[178] They also worry about the possibility that a revolutionary new technology will take them by surprise. What is the probability that countries can capitalize on their investments in nanotechnologies to change their geopolitical position in surprising ways? What are the implications for U.S. technological and military leadership?

National Innovative Capacity Matters

A broad group of scholars argue that, despite globalization, national characteristics define the nature of technological innovation and are critical to establishing and holding a technological edge. A number of such approaches in business administration, organizational sociology, economics, and political science give a central role to technology in attaining economic growth and military prowess.[179]

In economics, new approaches developed in the 1980s challenged core neoclassical microeconomic tenets underpinning the market-driven, *laissez faire* view.[180] These theories argue that technology, rather than capital and foreign direct investment, is the primary determinant of economic growth.[181] In contrast to neoclassical economic theories, technology is not a freely available public good in this view. Technology and knowledge are independent factors of production that shape a country's

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Magee and A. Galinsky, "Social Hierarchy: The Self-Reinforcing Nature of Power and Status," *The Academy of Management Annals* 2 (1):351-398 (2008)

[178] The literature on revolutions in military affairs (RMA) is large. For a small sample, see: (J. Arquilla and S. M. Karmel, "Welcome to the Revolution … In Chinese Military Affairs," *Defense & Security Analysis* 13:255-269 (1997); A.H. Bernstein and M. Libicki , "High-Tech: The Future Face of War? A Debate." *Commentary* 105:28-31 (1998); Thomas G. Mahnken, *Technology and the American way of war since 1945*. Edited by Inc ebrary. (New York ; Chichester, UK: New York ; Chichester, UK : Columbia University Press, 2010)

[179] In addition to the sources in note 185, see Lynn Eden, *Whole World on Fire: Organizations, Knowledge, and Nuclear Weapons Devastation* (Ithaca, NY: Cornell University Press, 2004); Donald Mackenzie, *Inventing Accuracy: A Historical Sociology of Nuclear Missile Guidance* (Cambridge, MA: MIT Press, 1990)

[180] These neoclassical microeconomic assumptions include the existence of perfectly competitive markets and freely and publicly accessible technology, the law of diminishing returns, and the centrality of capital accumulation for economic growth For a useful review, see Robert Gilpin, *Global Political Economy* (Princeton: Princeton University Press, 2001) pp. 103-128.

[181] Giovanni Dosi, "Sources, Procedures, and Microeconomic Effects of Innovation," *Journal of Economic Literature* 26 (3):1120-1171 (1988)

comparative advantage.[182] Indeed, technology tends to be under-provided due to market failure: An individual firm's investment in R&D spills over and becomes a public good for other firms in the economy, so the social rate of return on investment is more than double the investing firm's private rate of return. Firms therefore tend to underinvest in research and development, as they are unable to collect the full benefits of their investment.[183]

These approaches highlight, for differing reasons, that government support for technological innovation is necessary for economic growth and national security, and that government policy can fundamentally shape a country's international technological position. Neo-mercantilist and realist theories in their simplest form suggest that nations should seek to invent and manufacture advanced military technologies on their own and build a scientific workforce capable of producing them. Indigenous technological development is to be supported through trade barriers and national industrial policies providing subsidies and other incentives for technological research and development (R&D). Failing this ideal of technological autarchy, states should beg, borrow, and steal scientists and technologies from more advanced countries in order to catch up and overtake them. In this view, technologies are to be safeguarded and kept from enemies and potential adversaries through various forms of control, from secrecy to banning or limiting exports to intellectual property rights. Technological innovation and diffusion produces competition among states jockeying for survival, economic, military, and political dominance, and prestige.[184]

Other approaches to technological innovation understand that technological change is endogenous to the socio-economic and political system that produces it. While traveling under different labels in different academic disciplines, these approaches all pay attention to the social embeddedness of S/T innovation—the social and political structures and norms that foster technological change and, critically, its societal and commercial uptake.[185] Technological change and dominance therefore is

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[182] Paul M. Romer, "Increasing returns and long-run growth." *Journal of Political Economy* 94:1002 (1986); Paul Krugman, "Pricing to Market when the Exchange Rate Changes," *NBER Working Papers*: National Bureau of Economic Research, Inc (1986); Paul Krugman, "Increasing Returns and Economic Geography," *Journal of Political Economy* 99 (3):483 (1991)

[183] Paul M. Romer, "The origins of endogenous growth. (models for studying growth)," *Journal of Economic Perspectives* 8 (1):3 (1990)

[184] Robert Gilpin, *War and change in world politics*. (Cambridge, MA: Cambridge University Press, 1981)

[185] A.D. Chandler, *The Visible Hand: The Managerial Revolution in American Business* (Cambridge, MA: Belknap Press, 1977); James Hughes, G. Sasse, and C. Gordan, *Europeanization and Regionalization in*

not simply caused by the invention or possession of a technology, but brought about through human choices and changes in social and political institutions that foster technologies and enable their use and diffusion.[186] For example, Lynn White's *Medieval Technology and Social Change* (White 1964) highlights that gunpowder and cannon-making as technologies were widely diffused among Chinese, Europeans, Byzantines and Muslims, but it was only European conditions that led its leaders to apply these technologies to warfare in a systematic and successful fashion and establish Europe's global dominance.[187] A whole literature on national innovation systems (NIS) and varieties of capitalism highlights the various national forms of economic, political and social organization that can foster economic advancement, despite the globalization of market forces and actors.[188] Some have focused on the development of subnational technology clusters, such as Silicon Valley and Route 128 in Boston, that have generated regional high tech economies.[189] Existing social, political, educational, financial, and economic institutions and networks enable leaders to lock in their advantage, and ensure an ongoing technological edge over followers, creating a persistent core-

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the EU's Enlargement to Central and Eastern Europe: The Myth of Conditionality (London: Palgrave Macmillan, 2004); Donald Mackenzie, *Inventing Accuracy: A Historical Sociology of Nuclear Missile Guidance* (Cambridge, MA: MIT Press, 1990); J. R. Hollingsworth and R. Boyer, *Contemporary Capitalism: The Embeddedness of Institutions* (Cambridge, MA: Cambridge University Press, 1997); S. Bartholomew, "National Systems of Biotechnology Innovation: Complex Interdependence in the Global System," *Journal of International Business Studies* 28 (2):241-266 (1997)

[186] Richard R. Nelson, *An evolutionary theory of economic change*. Edited by Sidney G. Winter, *Economic change* (Cambridge, Mass.: Belknap Press of Harvard University Press, 1982); G. Dosi, K. Pavitt, and L. Soete, *The Economics of Technical Change and International Trade* (London, UK: Harvester Wheatsheaf, 1990); Keith Pavitt, "The Social Shaping of the National Science Base," *Research Policy* 27 (8):793–805 (1998)

[187] For this interpretation of White, see (Keith Krause, *Arms and the State* (Cambridge, MA: Cambridge University Press, 1995)

[188] On NIS, see C. Freeman, "The National System of Innovation in Historical Perspective," In *Technology, Globalization, and Economic Performance*, edited by D. Archibuigi and J. Michie (Cambridge, MA: Cambridge University Press 1997); on varieties of capitalism, see among others, (Chalmers Johnson et al., *Politics and productivity : the real story of why Japan works* (Cambridge, Mass.: Ballinger. 1989); Alice Amsden, J. Kochanowicz, and L. Taylor, *The Market Meets Its Match: Restructuring the Economies of Eastern Europe* (Cambridge, MA: Harvard University Press, 1994); John Zysman and Laura D'Andrea Tyson, *American industry in international competition : government policies and corporate strategies*, *Cornell studies in political economy* (Ithaca: Cornell University Press, 1983); Roselyn Hsueh, *China's regulatory state : a new strategy for globalization*, *Cornell studies in political economy* (Ithaca: Cornell University Press, 2011)

[189] Annalee Saxenian, *Regional Advantage: Culture and Competition in Silicon Valley and Route 128* (Cambridge, MA: Harvard University Press, 1994)

periphery structure in the international economy.[190] In this view, technology fosters international hierarchies that designate core, periphery and semi-periphery states and that are path-dependent and likely to be self-reinforcing.[191]

Governments, as a result, have a fundamental role in providing public investment in science and R&D in order to ensure that it occurs. Furthermore, governments can create a competitive national advantage through such public stimulation of R&D.[192] In this view, intangible investment in knowledge accumulation (through support for public education, basic R&D, and science, technology, engineering, and mathematics (STEM) education) is the primary determinant of economic growth.[193]

Among those analyzing the state's role in fostering technological advancement, the question of whether S/T change can lead technological laggards to surpass leaders is a matter of debate.[194] Simple technological borrowing or transfer is insufficient to allow technological laggards to catch up with, let alone surpass technological leaders.[195] Even skeptics, however, suggest that if technologically lagging countries are able to capture truly revolutionary technologies, they can leap ahead of dominant countries and change the international pecking order.[196] This raises the stakes for states when a new, potentially revolutionary technology, such as nanotechnology, emerges.

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[190] M. Porter, C. Freeman, S. Nelson, K. Winter, K. Pavitt, G. Dosi, and P. Krugman, *The Geography of Trade* (Cambridge, MA: MIT Press, 1991); For a useful review of the organizational theory literature discussing incumbent- vs. start-up-firm advantages and disadvantages in introducing radical vs. incremental innovations, see V. Mangematin, K. Errabi, and C. Gauthier, "Large Players in the Nanogame: Dedicated Nanotech Subsidiaries or Distributed Nanotech Capabilities?" *Journal of Technology Transfer* 36:640–664 (2011)

[191] Paul Krugman, "Increasing Returns and Economic Geography," *Journal of Political Economy* 99 (3):483 (1991)

[192] Michael Porter, *The Competitive Advantage of Nations* (New York, NY: Free Press, 1990)

[193] World Bank, World Development Report 1991, 33-5, (Freeman, "The National System of Innovation in Historical Perspective," *Technology, Globalization, and Economic Performance*, edited by D. Archibuigi and J. Michie (Cambridge, MA: Cambridge University Press, 1997);

194 (J. P. Singh, *Leapfrogging Development: The Political Economy of Telecommunications Restructuring* (Albany, NY: SUNY Press 1999)

[195] Elise S. Brezis, Paul R. Krugman, and Daniel Tsiddon, "Leapfrogging in International Competition: A Theory of Cycles in National Technological Leadership," *The American Economic Review* 83 (5):1211-1219 (1993)

[196] Ibid.

Whether nanotechnology threatens U.S. technological dominance, this literature suggests, requires considering the broader national and global context of innovation that countries face. If we consider the investments that the United States and others are making in nanotechnology, these national and global dimensions are likely to be decisive in both capturing and controlling the lion's share of benefits from technological innovation and controlling other countries' access to them.

U.S. National Competitiveness in Nanotechnology

The U.S. NNI has been assessed several times within its history, and one of the more recent assessments maintains that the US may be losing its competitive edge to innovative and R&D activity in Asian countries, particularly China.[197] This section evaluates U.S. relative competitiveness, with an eye to assessing whether this pessimism is warranted, given the literature on national innovation and concerns about the accuracy of the data on nanotech.

Through 2009, global government expenditures in nanotechnology were estimated to have reach $50 billion, when USG investment fell behind that of the leaders (EU and Russia), and held par with that of China (see Figure 5, p. 66). U.S. companies continue to lead in private nanotech R&D—with roughly $2 billion invested—closely followed by the Japanese private sector (see Figure 6, p. 66). The National Research Council[198] noted that the Battelle/R&D Magazine's 2012 Global R&D Funding Forecast predicted that the U.S. share of total global R&D would decrease from 32.8% in 2010 to 31.1% in 2012, and that the nations of Asia were expected to grow in funding, potentially posing long-term challenges to U.S. competitiveness.[199] Based on measures of "nanotech activity" and "technology development strength," Lux Research suggested in 2010 that the great powers of small-scale are Japan, Germany, Korea and Taiwan, while Singapore, Sweden, Korea, Israel and Switzerland dominate in particular nanotech niche markets. The United States, in their report, was slipping into "ivory tower status" as it fell behind on overall technology development capacity.

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[197] PCAST, "Report to the President and Congress on the Fourth Assessment of the National Nanotechnology Initiative. President's Council of Advisors on Science and Technology" (2012)
[198] National Research Council, "Triennial Review of the National Nanotechnology Initiative" (National Academy Press, 2013)
[199] Battelle, "2013 Global R&D Funding Forecast" (2012); Battelle, "2014 Global R&D Funding Forecast" (2013)

Russia is ranked along with Brazil and India as being in the "minor leagues."[200] Cientifica, on the other hand, in 2011 ranked the United States, followed by China, Russia, Germany and Japan as the countries where nanotech spending is most effectively transferred into economic activity.[201] Such conflicting reports stem from the problematic data collection and measurement discussed earlier.

Figure 5 and Figure 6 illustrate the 2008-2010 national investments of the ten countries that spend the most publicly and privately on nanotechnology, based on Lux Research data. Governmental officials pay close attention to these numbers. While the figures demonstrate that the United States leads in both government and private expenditures on nanotechnology, Russia and China are increasing public investment, while U.S. government spending is declining relative to 2009. The U.S. Congressional Research Service, also relying on Lux Research estimates, reported in its latest update on nanotechnology that U.S. Government investment is falling behind that of China and Russia on a purchasing power parity basis, but is still leading in real dollar terms. U.S. companies continue to lead in private nanotech R&D—with roughly $2 billion invested—closely followed by the Japanese private sector.[202]

The U.S. President's Council of Advisors on Science and Technology reported in 2012 that, "there has been concern that in addition to China, South Korea, and other early movers, the Russian Nanotech Corporation (RUSNANO) is now also rising as a major player, second only to the United States in its nanotechnology R&D spending. According to Lux Research, RUSNANO increased its funding by nearly 40 percent to $1.05 billion and has plans to increase even further to nearly $1.5 billion by 2015."[203] The U.S. government is closely tracking RUSNANO's activities, particularly its funding and acquisition of U.S. nanotech startups, even while admitting that RUSNANO's projects "don't make sense" both in terms of investments and return on investment. Russia's investment is

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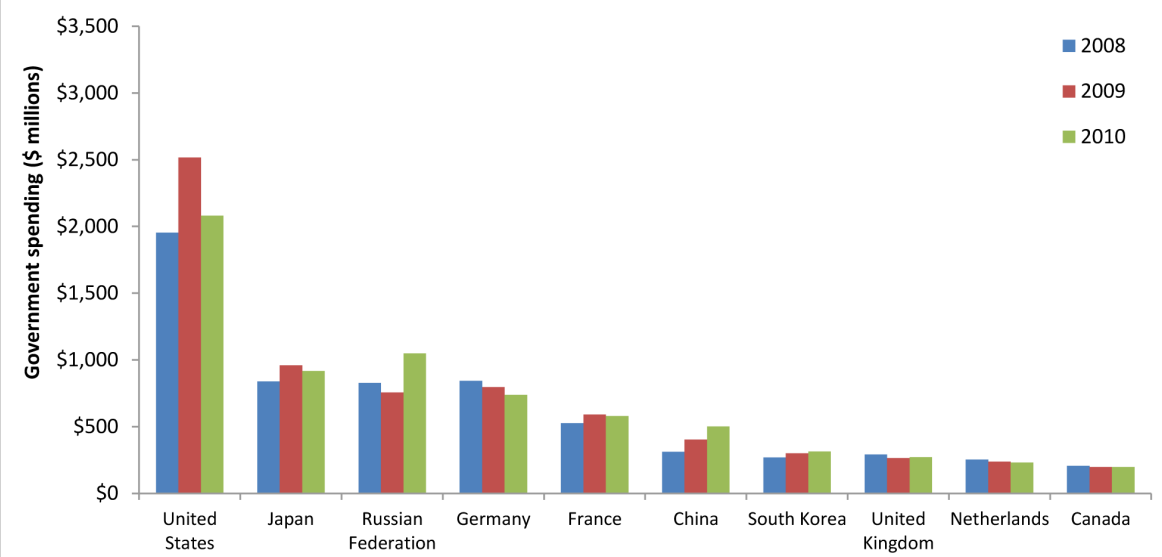
[200] D. Hwang, "Ranking the nations on nanotech," *Solid State Technology* (2010); Jaideep Raje, "Commercialisation of Nanotechnology: Global Overview and European Position," Lux Research (2011)
[201] Cientifica, " Global Funding of Nanotechnologies and Its Impact" (2011)
[202] John F. Sargent, Jr., "Nanotechnology: a policy primer.(Congressional Research Service)(Report)" (2010)
[203] PCAST, "Report to the President and Congress on the Fourth Assessment of the National Nanotechnology Initiative. President's Council of Advisors on Science and Technology" (2012), p. 13.

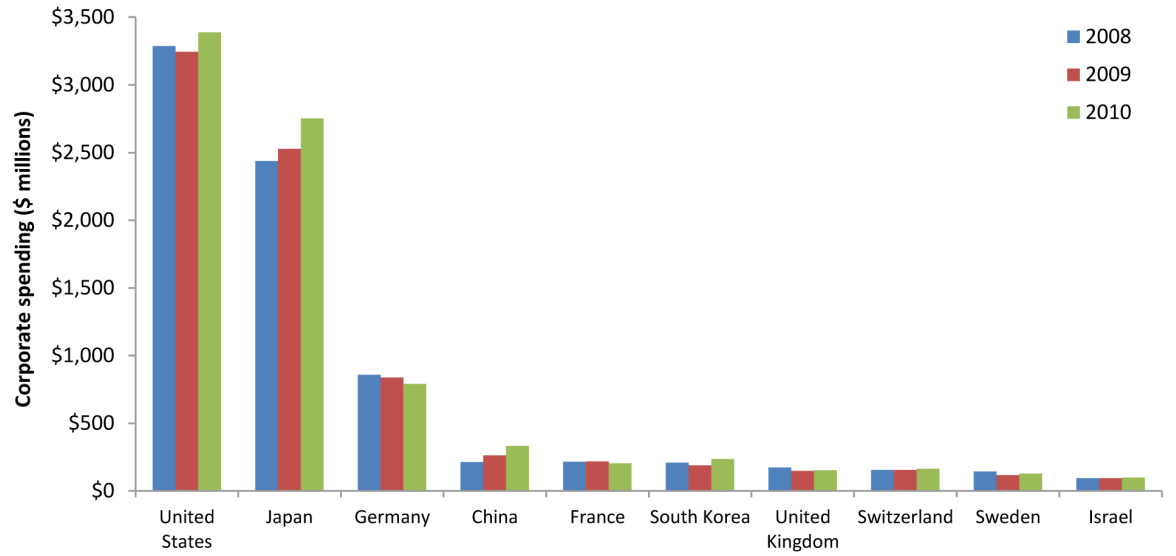
Figure 5. National investments in nanotechnology for top ten countries



Source: A. Xue and D. Hwang, "Nanotechnology Funding: Corporations Grab the Reins," *Lux Research,* April 2011.

Source: Reproduced from PCAST 2012 Report, p. 14.

Figure 6. Corporate spending on nanotechnology for top ten countries



Source: A. Xue and D. Hwang, "Nanotechnology Funding: Corporations Grab the Reins," *Lux Research,* April 2011.

Source: Reproduced from PCAST 2012 Report, p. 14.

not being matched by a commensurate increase in Russian nanotechnology publications or patents, both indicators of innovation and intellectual property rights.[204] Similar attention is being paid to Chinese nanotech efforts.[205]

Generally, the United States can still be characterized as the leader in the nanotech field. The U.S. President's proposed 2014 Federal Budget provides more than $1.7 billion for the National Nanotechnology Initiative (NNI), reflecting stable maintenance of the U.S. government investment in nanotech since its establishment in 2000. The three largest recipients of NNI are the Department of Defense, National Science Foundation, and the Department of Energy.[206] The cumulative U.S. NNI investment since fiscal year 2001, including the 2014 request, now totals almost $20 billion. U.S. leadership in nanotech is reflected not only in quantity of funding and intellectual property being developed in nanotechnology, but also in quality. Priority patents (Figure 3, p. 36) are where the intellectual property holder is internationally recognized as the first to file and gains the exclusive right to claim, albeit for a limited time, that intellectual property. "Priority patent applications indicate which countries will successfully hold the intellectual property pertaining to a technology patent family."[207] Another indicator of quality is number of citations a publication receives. Figure 7 below shows the number of citations of nanotechnology articles by lead author's country. The figure shows that, while China surpassed the United States in applying for patents (Figure 2, p. 36) and publications (Figure 4, p. 38), the most widely cited publications are those authored in U.S. and Europe. The number of citations and publications on nanotechnology in three of the most prestigious scientific journals, *Nature*, *Science*, and the *Proceedings of the National Academy of Sciences*

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[204] PCAST, "Report to the President and Congress on the Fourth Assessment of the National Nanotechnology Initiative. President's Council of Advisors on Science and Technology" (2012); Evegeny A. Klochikhin, "Innovation System in Transition: Opportunities for Policy Learning between China and Russia," *Science and Public Policy* 40, pp. 657-673 (2013). For detailed analyses of Russia's nanotechnology efforts, see F. Westerlund, *Russian Nanotechnology R&D: Thinking Big about Small Scale Scie*nce, (Stockholm: Swedish Defense Research Agency, 2011); R. Roffey, "Russian Science and Technology is Still Having Problems—Implications for Defense Research," *Journal of Slavic Military Studies* 26 (2):162-188 (2013).

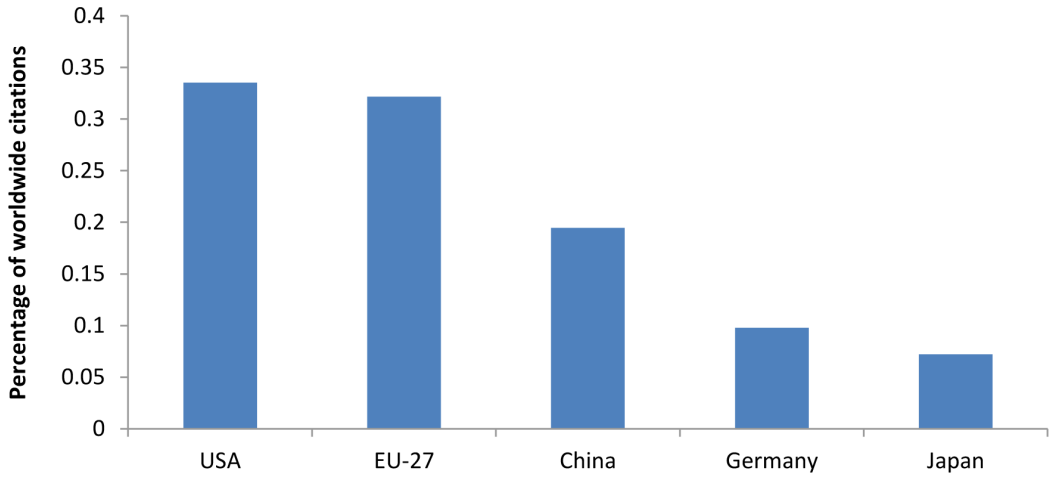
[205] Anne Clunan, personal communication with senior officials on the U.S. NSET Subcommittee, May 31, 2013.

[206] Matthew N. Eisler, "Department of Energy," In *Encyclopedia of Nanoscience and* Society, edited by David H. Guston (Thousand Oaks, CA: Sage, 2010), p. 154.

[207] PCAST, "Report to the President and Congress on the Fourth Assessment of the National Nanotechnology Initiative. President's Council of Advisors on Science and Technology" (2012), pp. 5-6.

suggest that Americans and Europeans are publishing the highest quality articles on nanotechnology. "The U.S. and EU-27 exhibit a large publication lead in these journals compared to their Asian counterparts and hold a dominate [sic] position in terms of global publishing rate."[208] What these data mean for nanotechnology's potential to disrupt the global hierarchy of economic and military power is discussed below.

Figure 7. Percentage by country of global citations for nanotechnology articles



Source: L. Kay, P. Shapira, J. Youtie, and A. L. Porter, Program on Nanotechnology Research and Innovation System Assessment Georgia Institute of Technology, Atlanta, Georgia, with support from the National Science Foundation (NSF) through the Center for Nanotechnology in Society (Arizona State University; Award No. 0937591) [Data as of January 2010].

Notes: Search based on S. Arora, A. L. Porter, Y. Youtie, and S. Shapira, Capturing new developments in nanotechnology scientific output: A search strategy for publication records. STIP White Paper, Atlanta, Georgia, 2011. This figure shows percent distribution for nanotechnology publications in 2009 as of 22 August 2011.

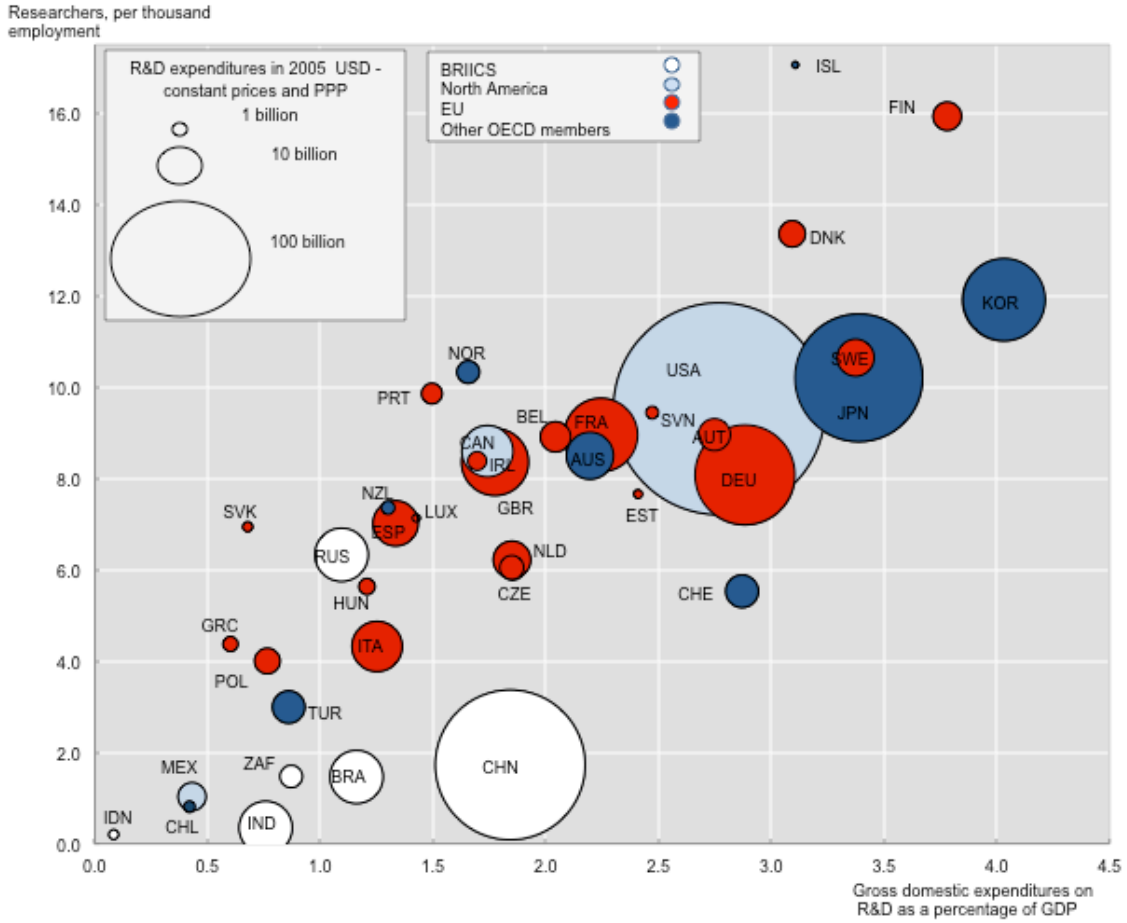
Source: Reproduced from President's Council of Advisors on Science and Technology (PCAST) 2012 Report, p. 35.

A wide array of data on competitiveness and innovation-readiness provides the national context in which government bets on nanotechnology play out. New technologies are only likely to truly revolutionize an economy and society if there is a broader national base that allows that technology to spread and transform from its initial niche application. Several factors shape such an outcome, including the quality of the country's higher educational system, business sector sophistication, property rights system, infrastructure, in addition to intellectual property outputs, such as patents

[208] Ibid, p. 35.

and scientific articles. Figure 8, below, shows the overall R&D intensity of the OECD countries, as well as Brazil, Russia, India and China in 2011.

Figure 8. R&D in OECD and key partner countries, 2011

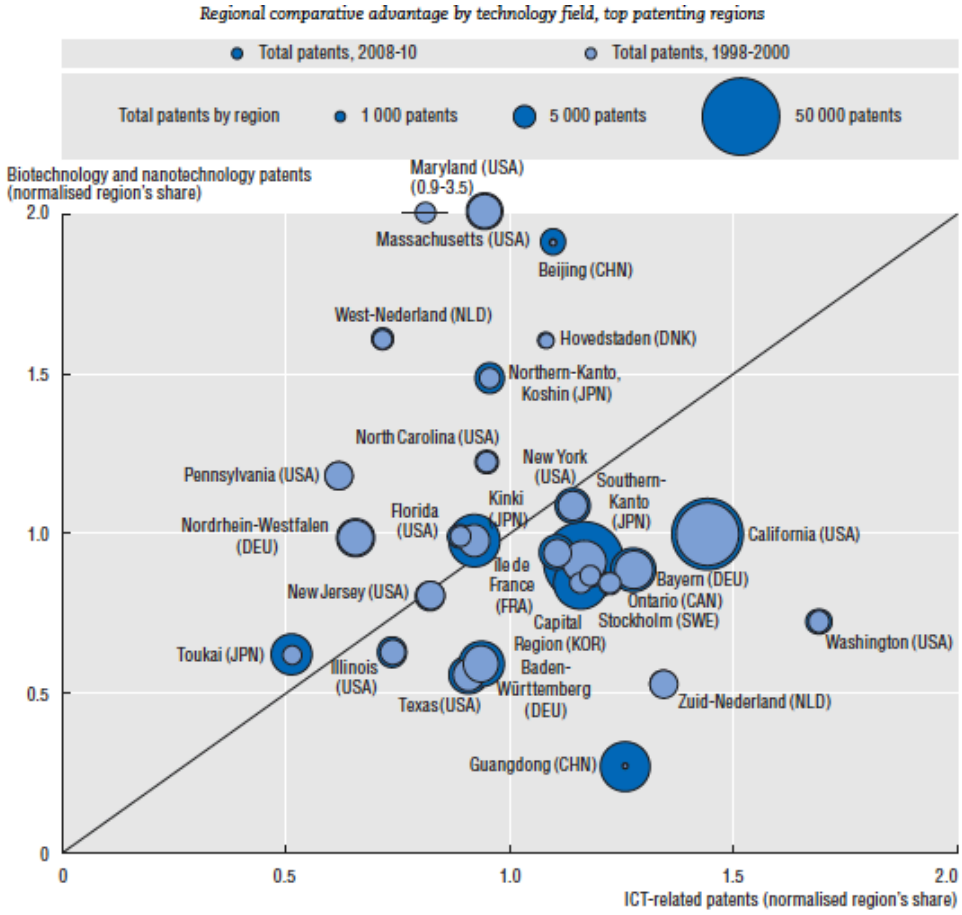


Source: OECD Science, Technology, and Industry Scorecard 2013, p. 50.

Regionally, location matters in terms of generating innovation economies. The OECD has documented that only a few countries, particularly the United States and Japan, are home to many of the top knowledge intensive industries (information and communications technology, biotechnology, and nanotechnology). Figure 9 shows the location of regions that are leaders in the production of patents in biotechnology, ICT, and nanotechnology over time. What this figure suggests is that if we assume that early patents are more likely to reflect core intellectual property in these sectors and later patents reflect derivative intellectual property, then the United States and its allies remain technological leaders. Countries with significant innovation "hot spots" in these

technologies include the United States, Germany, Japan, Sweden, the Netherlands, France, Korea, China appears on this map after 2008, while Russia, India and Brazil do not register at all.[209] Russia, China, and India, in an effort to catch up, have all adopted the Western business model of "technology clusters", with highly visible outlays for new nanotechnology research parks in Skolkovo, Suzhou, and Bangalore, respectively.[210]

Figure 9. Innovation Hotspots in ICT, Biotechnologies, and Nanotechnologies, 1998-2000 and 2008-2010



Source: OECD STIS 2013, p. 55.

[209] OECD, " OECD, Science Technology, and Industry Scorecard" (2011), p. 55.
[210] The OECD produces a technology cluster scorecard (Ibid.). For presentations on national nanotechnology clusters, see the following: China: http://www.euronanoforum2011.eu/wp-content/uploads/2011/09/enf2011support-commercialisationzhangfin.pdf; India: http://aulavirtual.icex.es/doc/Seminario263/exporta08sem2sharmadiapos.pdf.

A number of organizations have developed indices of relative economic and technological advancement and innovativeness. These include the World Bank's Knowledge Economy Index (KEI) and Knowledge Index (KI). The KI measures a country's capacity to "generate, adopt and diffuse knowledge," while the KEI measures whether the country's environment is "conducive for knowledge to be used effectively."[211] The Knowledge Index lists the United States 9th, Germany 10th, the U.K. 16th, Japan 18th, Russia 43rd, Brazil 55th, China 86th, and India 115th in terms of ability to generate, adopt and diffuse knowledge. In terms of a knowledge-ready environment, the KEI ranked Germany 8th, the United States 12th, the United Kingdom 14th, Japan 22nd, Russia 55th, Brazil 60th, China 84th 109th. Two other indices, the Global Innovation Index (GII) and the Global Competitiveness Index (GCI) also shed light on national capabilities to create and adopt new knowledge and technologies.[212] In 2013, the Global Innovation Index Report ranked the United States, United Kingdom, Germany and Japan as the top four innovators (in that order) in terms of quality, which in turn is based on quality of universities, patents and citations. China ranked in 19th place, with Brazil edging out Russia for 25th place, and India in 31st.[213] China and India are categorized as efficient learners in innovation, with Brazil lagging them slightly. Russia, on the other hand, underperforms in innovation relative to its GDP. The United States, United Kingdom, Japan, and Germany are all in characterized as innovation leaders relative to GDP.[214] The GCI has a similar ranking for overall competitiveness and innovation-readiness.**Error! Reference source not found.** Germany, Japan, the U.S., and U.K. all rank in the top ten on innovation and sophistication factors; Russia, ranked 99th, is far outpaced by China (34th), India (41st), and Brazil (44th).[215]

Nationally, it appears that Russia, in particular, Brazil, and India are the least prepared to profit from the invention of a revolutionary nanotechnology that would enable them to leap ahead of more advanced economies.[216] Russian officials admit that they are three to four decades behind the West

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[211] World Bank, KEI and KI Indexes: World Bank, " Knowledge Assessment Methodology" (2012), (KAM 2012)

[212] Global Innovation Index Report (2013). The Global Innovation Index is published jointly by Cornell University, INSEAD and the World Intellectual Property Organization (WIPO), while the Global Competitiveness Index is a publication of the World Economic Forum.

[213] Ibid., p. 26

[214] *Global Innovation Report 2013 | The Global Innovation Index* (2013), p. 24

[215] GCI Data Platform: World Economic Forum, "Global Competitiveness Index 2013" (2013).

[216] F. Westerlund, *Russian Nanotechnology R&D: Thinking Big about Small Scale Science* (Stockholm: Swedish Defense Research Agency, 2011); R. Roffey, "Russian Science and Technology is Still

in terms of technology development, and that their country lacks favorable conditions for innovation.[217] China is now the second largest R&D performer, behind the United States, which performs twice the amount of R&D as that done in China. Of the top fifty universities in the world, thirty-four are in the United States, with two for the first time appearing outside of the OECD, in Taiwan. The remainder lies in Western Europe.[218]

These data suggest that the national context for innovation greatly matters for the impact nanotechnologies are likely to have on national economic competitiveness and national security. Expectations that nanotechnology investment will allow those with a weak innovation environment to catch up to and surpass technological leaders in the OECD seem overblown. A broader innovation base gives these countries a lead that is difficult to surpass.

Globally, the internationalization of R&D and production appear to further undermine assumptions a country's ability to leap-frog via indigenous development and/or commercialization of a new technology, even a revolutionary one, to the top of the technological hierarchy. International scientific and research collaboration is becoming a hallmark of a country's categorization as knowledge economy. The OECD has calculated that among large firms, collaboration in innovation reaches as high as seventy percent in the some of the most technologically advanced countries, while collaboration among small and medium enterprises only ranges from 20-40%. Market sources of collaboration (i.e., suppliers, customers, and competitors) far outstrip institutional sources (higher education and government).[219] This means that countries with underdeveloped or relatively weak business sophistication, such as Russia,[220] are likely at a pronounced disadvantage in accessing and diffusing innovative technologies domestically.

Having Problems—Implications for Defense Research," *Journal of Slavic Military Studies* 26 (2):162-188 (2013)

[217] Anatoly Chubais, head of RUSNANO, quoted in Andrew Kramer, "Russia Plans to Promote Technology Innovations," *The New York Times*, February 4, 2010; Lyubov Pronina, "Russia, a high-tech laggard, aims to change that," *The New York Times* November 30, 2007; and Andrew Kramer, "Competing Visions for Russia's Economic Future," *The New York Times* May 22, 2014.

[218] OECD, "OECD, Science Technology, and Industry Scorecard," 2011, pp. 50, 54.

[219] Ibid., p. 124.

[220] R. Roffey, "Russian Science and Technology is Still Having Problems—Implications for Defense Research," *Journal of Slavic Military Studies* 26 (2):162-188 (2013)

International collaboration is also a significant source of economic competitiveness that can allow a country's firms to access to a wider range of knowledge and resources at lower cost and risk.[221] Brazil, Russia, and Japan rely heavily on national partners, whereas other countries display more balance between national and international.[222] International mobility in researchers also suggests the difficulty of national attempts to create and hold onto a technological edge. Scientific brain drain tends to augment the strength of technological leaders, particularly the United States. In terms of net bilateral flows, the OECD calculates that Russia lost 61%, India 32%, and Japan 17% of its scientific authors to the United States during the 1996-2011 period. Japan has seen a net loss of 47% of scientific authors to China. In contrast, China and Korea have reversed brain drain, gaining 3% and 24% respectively more scientific authors than the United States during the same period.[223]

The exception here is the United States, as it attracts the highest number of scientists and researchers from abroad, reducing the need for external collaboration. The United States has the least amount of international collaboration, but the highest quality with respect to top-cited publications from 2003-2011.[224] Similarly, the U.S.-based authors "account for more than a third of all scientific documents cited in patents in the areas of biotechnology, health, nanotechnology, ICT [information and communications technology] and environment," revealing its broad and fairly balanced basis for knowledge transfer to the economic innovation system. China, Japan, and Korea have a degree of specialization in nanotechnologies, relative to the United States, which has somewhat more specialization in ICT than the other fields.[225] Finally, many of the metrics and technology forecasts on nanotechnology take a decidedly state-centric starting point. Far fewer studies emphasize the role that global R&D alliances and networks play in nanotech development.[226]

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[221] OECD, "OECD, Science Technology, and Industry Scorecard," 2011, pp. 128-129.
[222] Ibid., pp. 128-129.
[223] OECD, "Regulatory Frameworks for Nanotechnology in Foods and Medical Products: Summary Results of a Survey Activity," In *OECD Science, Technology and Industry Policy Papers No. 4* (Paris, France: OECD Publishing, 2013), p. 132.
[224] OECD, "OECD, Science Technology, and Industry Scorecard," 2011, pp. 133-135.
[225] Ibid., p. 136.
[226] Most of the literature is about R&D more generally. See UNCTAD, "World Investment Report 2005: Transnational Corporations and the Internationalization of R&D" (2005); National Resesarch Council, "Globalization of Materials R&D: Time for a National Strategy," Washington, DC (2005); John H. Dunning and S. M. Lundan, "The internationalization of corporate R&D: a review of the evidence and some policy implications for home countries," *The Review of Policy Research* 26 (1 2):13 (2009).

Yet what research is done displays significant transnational collaboration on nanotech R&D, with the United States as the central hub in the network.[227] There is extensive collaboration between U.S. and Chinese scientists on nanotechnology, as well as among other countries.[228]

The United States is unlikely soon to be displaced by China or emerging economies in the nanotechnology sector. The United States was an early pioneer in nanotech development, as indicated by the 1996 Nobel Prize awarded to Richard Smalley for the discovery of fullerenes. The United States also remains ahead in terms of commercialization, although concerns among U.S. officials that Asian countries are rapidly catching up should not be dismissed.[229]

VI. Conclusion: Nanotechnology as (Tentatively) Revolutionary

Is nanotechnology revolutionary? As this report shows, nations are busily placing bets that nanotechnology will radically alter their position in the international system; whether these bets are well placed depends on whether or not nanotech is truly revolutionary.[230] The problem with forecasting technological revolutions is that they are only predictable in hindsight, so our conclusions must be considered tentative.[231]

There are different views on what constitutes technological revolution and disruption. Where political scientists and historians speak of technological revolutions, the business and economics literatures refer to disruptive and general-purpose technologies. Political scientists and historians are concerned with a broader phenomenon—socio-political and economic reorganization that is part cause and consequence of technological innovation, a concept more in keeping with the introduction of a new "general purpose technology," rather than a disruptive or sustaining one.[232] In business and economics, a general-purpose technology has "substantial and pervasive effect across

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[227] NSF, *Science and Engineering Indicators 2012* (2012).
[228] Philip Shapira and Jue Wang, "Follow the Money," *Nature* 486 (2 December 2010): 627-628.
[229] Anne L. Clunan, personal communication with Mihail Roco, Washington, DC, May 30, 2013.
[230] Elise S. Brezis, Paul R. Krugman, and Daniel Tsiddon, "Leapfrogging in International Competition: A Theory of Cycles in National Technological Leadership," *The American Economic Review* 83 (5):1211-1219 (1993)
[231] R. Kostoff, R. Boylan, and G. Simons, "Disruptive Technology Roadmaps," *Technological Forecasting and Social Change* 71 (1-2):141–159 (2004)
[232] Erwin Danneels, "Disruptive Technology Reconsidered," *The Journal of Product innovation management* 21 (1):246-258 (2004)

the whole of society."[233] "Disruptive technologies", in contrast, "provide dramatic improvements to current product market paradigms, or produce the physical and service products that initiate new industries. These regime changes define a new product platform, which is far different from what the market would have experienced with 'only' incremental innovation."[234] Incremental innovation, on the other hand, incorporates new "sustaining technologies … that improve the performance of established products through the current technology product paradigm."[235] A disruptive technology only gradually gains adherents, until such a time as some tipping point is reached, and the technology displaces others.[236] A 2008 U.S. National Intelligence Council report, in contrast, defined disruptive technologies as simply those having the potential to degrade or enhance one or more of the following elements of national power: geopolitical, military, economic, and social cohesion.[237]

At present, despite the definitional and data problems discussed earlier, we tentatively conclude that nanotechnology will be revolutionary, if it is widely adopted. Our tentativeness stems from ongoing debate over whether nanotech will revolutionize economy and society. A current, sober, academic assessment is that nanotech does appear to have the characteristics of a general-purpose technology, and therefore may be considered revolutionary in social and political spheres beyond its economic applications.[238] U.S. officials focused on nanotechnologies, however, do not agree on whether nanotechnologies are revolutionary. Some view them as largely incremental, while others highlight that only particular commercial sectors—medicine and energy (especially solar)—would see disruption. Electronics and materials science nanotechnologies are viewed as more evolutionary than

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[233] On disruptive technology, see R. Kostoff, R. Boylan, and G. Simons, "Disruptive Technology Roadmaps," *Technological Forecasting and Social Change* 71 (1-2):141–159 (2004); on general purpose technology, see J. Youtie, M. Iacopetta, and S. Graham, "Assessing the Nature of Nanotechnology: Can We Uncover an Emerging General Purpose Technology?" *The Journal of Technology Transfer* 33 (3):315–329 (2007)

[234] R. Kostoff, R. Boylan, and G. Simons, "Disruptive Technology Roadmaps," *Technological Forecasting and Social Change* 71 (1-2):141–159 (2004), pp. 142-3

[235] Ibid., pp. 144.

[236] Erwin Danneels, "Disruptive Technology Reconsidered," *The Journal of Product innovation management* 21 (1):246-258 (2004)

[237] National Intelligence Council, "Disruptive Civil Technologies: Six Technologies with Potential Impacts on US Interests out to 2025," *Report CR 2008-07*: National Intelligence Council (2008), p. i.

[238] J. Youtie, M. Iacopetta, and S. Graham, "Assessing the Nature of Nanotechnology: Can We Uncover an Emerging General Purpose Technology?" *The Journal of Technology Transfer* 33 (3):315–329 (2007)

revolutionary.[239] Another assessment suggests that Asian countries that are betting heavily on nanomaterials and nanoelectronics are on an evolutionary path, as nanomanufacturing and bio-nanotechnology are the disruptive sectors.[240] Not surprisingly, U.S. investments in nanotechnology reflect a heavy investment in a core U.S. strength: the life sciences. China and Russia, in contrast, are strong in materials science, where it is unclear that new disruptive materials will emerge, although it is possible as yet-undiscovered nanomaterials may be revolutionary.

Nanotech is not a case of technological surprise for the United States. Dual-use technologies, including nanotechnology, however, rarely lead to strategic or tactical surprise.[241] U.S., European and Japanese research and development in nanotech has been ongoing for forty years, with substantial investments by the U.S. military and government prior to the 2000 establishment of the U.S. NNI. These investments have made the United States the leader in nanotechnology, so if there is a basis for surprise, it is for countries such as Russia that effectively dropped out of technological competition for the twenty years following the end of the Cold War, or China and India, which only began to seriously embrace nanotechnology at the outset of the twenty-first century. While China's overall R&D growth is notable and impressive,[242] in nanotechnology, it still lags in quality. The central issue with respect to surprise is how non-state actors may apply nano-enabled technologies for malfeasant ends, an issue beyond the scope of this study that requires further research.

Applications of nanotech are already widespread in defense, electronics, energy, some consumer products, and are becoming so in medicine. There is limited potential for surprise in the form of mass destructive or disruptive effects from nanotechnology applications, with the caveat that new nanomaterials or novel nanobiological agents may be discovered. Nanotechnology compounds the existing difficulties in chemical and biological weapons proliferation, particularly with regard to synthetic creation of novel agents; but it makes up for this by offering significant gains in detection

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[239] Anne Clunan, personal communication with senior members of the U.S. NSET Subcommittee, May 30-31, 2013.

[240] K. Miyazaki and N. Islam, "Nanotechnology Systems of innovation—An Analysis of Industry and Academia Research Activities," *Technovation* 27 (11):661–675 (2007); I. Nazrul, and K. Miyazaki, "An Empirical Analysis of Nanotechnology Research Domains," *Technovation* 30 (4):229–237 (2010)

[241] Ronald F. Lehman, "Unclear and Present Danger: The Strategic Implications of Latent, Dual-Use Science and Technology," *Strategic Latency and World Power: How Technology Is Changing Our Concepts of Security,* Zachary Davis, Ronald F. Lehman, and Michael Nacht, editors. (Livermore, CA: Lawrence Livermore National Laboratory, 2014), p. 5.

[242] NSF, *Science and Engineering Indicators 2012* (2012), pp. 7-43.

and monitoring. Nanotech accelerates and integrates the already established trends towards miniaturization, automation, stealth, precision targeting, and energy efficiency. In life sciences, nanotechnology is creating a revolution in health care. Here, diagnosis and treatment are being increasingly tailored to the individual person, if not their individual cells. Life science applications to environmental remediation are aiming to eliminate hunger and potable water scarcity. In energy, the potential for cheap solar cells and improvements in energy storage point toward a post-carbon economy. This will dramatically affect defense applications in ways that differ from the ongoing trends to create smaller and smaller automated drones and personal digital devices capable of conducting all manner of military tasks. Much of nanotech's revolutionary promise in these fields is to reduce or even eliminate conflict over key resources, such as energy, food and water. The implications for national and global security would then be profound. The main surprise today arises from how pervasive nanotechnology already is, a fact of which the public is generally unaware.[243] The sum total of the social, economic and political impact of these technologies will fundamentally change society and the economy, if they are widely adopted.

Societal factors shape the up-take of new technologies and will affect nanotechnology's revolutionary potential. The history of technological revolution and technology adoption suggests that mere investment and invention is insufficient to launch a technological revolution.[244] Consumer and, more broadly, societal acceptance are necessary for technology to have a significant impact.[245] Nanotechnologies will only be revolutionary if they are taken up and widely commercialized.[246] This outcome is not certain, for two reasons. Nanotechnology has not been commercialized as quickly as forecast, as venture capitalists and private funders are concerned about the long time horizon between basic and applied R&D and scaling up to product development.[247] Firms and insurance companies are worried about societal acceptance, as nanotech has generated considerable concern

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[243] NSF, *Science and Engineering Indicators 2012* (2012), pp. 7-43.
[244] Keith Krause, *Arms and the State* (Cambridge, MA: Cambridge University Press, 1995); Robert Gilpin, *War and change in world politics* (Cambridge, MA: Cambridge University Press, 1981)
[245] J. Youtie, M. Iacopetta, and S. Graham, "Assessing the Nature of Nanotechnology: Can We Uncover an Emerging General Purpose Technology?" *The Journal of Technology Transfer* 33 (3):315–329 (2007)
[246] E. O'Rourke and M. Morrison, "Challenges for Governments in Evaluating Return on Investment from Nanotechnology and Its Broader Economic Impact," *OECD Background Paper*, (2012)
[247] Ibid.

about environmental, health, and safety impacts of nano-enabled products and nano-manufacturing processes.[248] There is considerable disagreement among the European Union, United States, Brazil, and China over both the statistical definition of nanotechnology, and the definition of industrial standards.[249] As toxicological studies are completed and nanotech's health, safety, privacy and environmental impacts become known, there is potential for public backlash against them, as happened in the EU over genetically-modified organisms. Such a backlash may significantly alter the commercial viability of various nanotech-enabled sectors, and provide an advantage for countries where nanotechnologies are generally viewed positively, which today include the United States and China.

KEY FINDINGS AND RECOMMENDATIONS

Nanotechnology is a general-purpose technology that is contributing to the ongoing revolution in information and communications technologies, microelectronics and robotics. The nature of warfare has already been dramatically transformed over the past thirty years with the increasing importance of precision-guided munitions, unmanned vehicles, and information dominance and surveillance. Nanotechnology dramatically extends and accelerates this trend. There is little evidence that nanotechnologies provide the basis for novel weapons of mass destruction or mass effect. Nanotechnology is converging with the chemical, biological and cognitive sciences in ways that promise to revolutionize human health and environment. Nanotechnology is likely to dramatically improve the health and resilience of armed forces personnel and the public and potentially even reduce resource scarcity as a cause of war. The United States remains a leader in nanotechnology, along with German and Japan, though other Asian countries, including China, are expanding and improving their nanotechnological base. In order to maintain this position, the USG should continue its investment in nanotechnology, with an ongoing sustained commitment to basic R&D and increased assistance in the commercialization of nanotech applications.

To date, there is little appetite or emphasis on governing the dual-use and military applications of nanotechnology at the multilateral or national levels. Nanotechnology poses the same challenges as

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[248] Philip Shapira and Jan Youtie, "The Economic Contributions of Nanotechnology to Green and Sustainable Growth" (2012)

[249] Anne Clunan, personal communication with senior member of the U.S. NSET Subcommittee, May 30, 2013.

biological technology with respect to its dual-use nature and governance challenges. With very few exceptions, no scholarly literature focuses on regulating military uses of nanotechnology.[250] The focus of national regulation has been on public health, safety and environment preservation.[251] Currently, countries are relying on existing nonproliferation and export control regimes to cover nanotechnologies. These regimes are ill-equipped to keep pace with the rapid advances in what is now an inherently trans-disciplinary science. One result has been the increasing devolution of responsibility for national security to corporations and individual scientists.[252] This push for self-regulation arises in large part from the tremendous difficulties in merely monitoring scientific activities that unwittingly can lead to weaponization of nanotechnology-enabled materials, pathogens, or delivery platforms. In the absence of appetite for either multilateral or national regulations, U.S. agencies should work with academics and corporations to foster a culture of nano-security and dual-use awareness and codes of conduct for research and development. As in biosecurity, some of the responsibilities for what managing the risk that peaceful materials will be used for nefarious purposes can be placed scientists themselves, through fostering awareness, dialogue, and cultural norms among scientists themselves. Such norms cannot substitute for governmental and intergovernmental cooperation to manage the dual-use risks from nanotechnology, and create international norms and governance mechanisms regarding their legitimate development and use. At present, however, without such governance regimes or established networks of information sharing and transnational cooperation among scientists,

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[250] John F. Sargent, Jr., *Nanotechnology and U.S. Competitiveness: Issues and Options*. Edited by Service Library Of Congress, Washington, D.C. Congressional Research (2008)

[251] In January 2012, the U.S. National Research Council issued a five-year research effort to assess the safety of nanotech materials. Expenditures devoted to understanding nanotechnology's implications have tended to focus on environmental and societal impacts, as seen in the National Science Foundation-funded centers on environmental implications of nanotechnology at Duke University and UCLA and on nanotechnology and society at Arizona University, University of California Santa Barbara and University of Southern California. See http://www.nano.gov/initiatives/government/research-centers.

[252] Margaret E. Kosal, "Strategy, Technology, and Governance: Shift of Responsibility from Nation-states to Individuals," Presentation prepared for delivery at the Society for the Study of Nanoscience and Emerging Technologies 5th Annual Meeting, Boston, MA, October 27-29, 2013

corporations and intelligence and security practitioners,[253] there is an ongoing need for the USG to continue to monitor closely nanotech developments domestically and abroad.

The problem of remaining aware of nanotechnology advances is only worsened by the questionable comparability and quality of existing indicators on nanotechnology R&D. It is necessary to collect more data on nanotechnology's military and commercial applications and health, safety, and environmental impacts, as well as for comparative analysis with analogous technologies that have had disruptive and/or revolutionary impacts. The U.S. government should encourage more interdisciplinary collaboration between scientists, policymakers, defense practitioners, and market actors to facilitate comparative longitudinal and cross-national data collection and measurement. It is important to gather not only the information available, but to ask the more difficult analytical questions about what the technologies mean, for whom, and how to assess the nature of the threats and opportunities from both a security and a competitiveness perspective. Another challenge is to integrate analyses from global supply chain analysis, to gain a better picture of how the globalization of defense and civilian nanotech production, as well as production networks of scientific research and manufacturing, may affect U.S. efforts to control illegitimate development and use of nanotechnology.

[253] Anne L. Clunan, "Building Information Networks for Biosecurity," *Terrorism, War or Disease? Unraveling the Use of Biological Weapons,* pp. 293-310, Anne L. Clunan, Peter R. Lavoy and Susan B. Martin, editors (Palo Alto: Stanford University Press, 2008)

List of Abbreviations

BMBF	Federal Ministry of Education and Research (Germany)
BRIC	Brazil, Russia, India and China
BWC	Biological and Toxin Weapons Convention
CAE	Chinese Academy of Engineering
CAS	Chinese Academy of Sciences
CBRNE	Chemical, Biological, Radiological, Nuclear and Explosive weapons
CCC	Naval Postgraduate School Center on Contemporary Conflict
CCP	Communist Party of China
CNANE	China National Academy of Nanotechnology and Engineering
CNITA	China Nonwovens & Industrial Textiles Association
CNTAC	China National Textiles & Apparel Council
COCOM	Coordinating Committee for Multilateral Export Controls
CWC	Chemical Weapons Convention
DURC	Dual Use Research of Concern
EDA	European Defense Agency
EHS	Environmental and Health Safety
EU	European Union
FDI	Foreign Direct Investment
GDP	Gross Domestic Product
IMF	International Monetary Fund
ISO	International Organization for Standardization
ISO TC	Technical Committee of the International Organization for Standardization
JIP	Joint Investment Programme
MFA	Multi-Fiber Arrangement
MLP	Medium- and Long-Term Plan for the Development of Science and Technology
MNC	Multinational Corporation
MOD	Ministry of Defense (United Kingdom)
MOE	Ministry of Education
MOST	Ministry of Science and Technology
NATO	North Atlantic Treaty Organization
NCNST	National Center for Nanoscience and Nanotechnology
NDRC	National Development and Reform Commission
NERCN	Shanghai National Engineering Research Center for Nanotechnology
NIBC	Nanotechnology Industrialization Base of China
NIS	National Innovation Systems
NNI	U.S. National Nanotechnology Initiative
NPT	Nuclear Non-Proliferation Treaty
NSA	Department of National Security Affairs
NSCNN	National Steering Committee of Nanoscience and Nanotechnology
NSF	National Science Foundation (United States)
NSFC	National Natural Science Foundation of China

OECD	Organization for Economic Co-operation and Development
PASCC	Project on Advanced Systems and Concepts for Countering WMD
PRC	People's Republic of China
R&D	Research and Development
RUSNANO	Russian Nanotech Corporation
S/T	Science and Technology
SATI	State Administration of Textile Industry
SCENIHR	Scientific Committee on Emerging and Newly Identified Health Risks of the European Commission
SIP	Suzhou Industrial Park
SNPC	Shanghai Nanotechnology Promotion Center
SSTC	State Science and Technology Commission
STEM	Science, Technology, Engineering, and Mathematics
STM	Scanning Tunneling Microscopy
TNC	Transnational Corporation
UN	United Nations
UNESCO	United Nations Educational, Scientific, and Cultural Organization
USG	United States Government
WMD	Weapons of Mass Destruction
WTO	World Trade Organization

REFERENCES

2013. *Global Innovation Report 2013 | The Global Innovation Index*.

(SCENIHR), Scientific Committee on Emerging and Newly Identified Health Risks of the European Commission. 2006. 3.1. Introduction: The Appropriateness of Existing Methodologies to Assess the Potential Risks Associated with Engineered and Adventitious Products of Nanotechnologies. European Commission.

Allen, George. 2005. "The Economic Promise of Nanotechnology." *Issues in Science & Technology* 2005 (Summer). Online: http://issues.org/21-4/allen/.

Altmann, Jürgen, and Mark Gubrud. 2004. "Anticipating military nanotechnology." *IEEE Technology and Society Magazine* 23 (4):33-40. doi: 10.1109/MTAS.2004.1371637.

Altmann, Jürgen. 2006. *Military nanotechnology : potential applications and preventive arms control*. New York: Routledge.

Amsden, Alice, Jacek Kochanowicz, and Lance Taylor. 1994. *The Market Meets Its Match: Restructuring the Economies of Eastern Europe*. Cambridge, MA: Harvard University Press.

Anand, Sudhir, Paul Segal, and Joseph E. Stiglitz. 2010. *Debates on the measurement of global poverty*, *The Initiative for Policy Dialogue series*. Oxford ; New York: Oxford University Press.

Appelbaum, R., Cao C., R. Parker, and Y. Motoyama. 2013. "Nanotechnology as Industrial Policy: China and the United States." Paper presented at the 2013 International Studies Association Annual Conference, San Francisco, CA.

Arquilla, J, and SM Karmel. 1997. "Welcome to the Revolution … In Chinese Military Affairs." *Defense & Security Analysis* 13:255-269.

Atlas, Ronald M., and Malcolm Dando. 2006. "The dual-use dilemma for the life sciences: perspectives, conundrums, and global solutions." *Biosecurity and bioterrorism : biodefense strategy, practice, and science* 4 (3):276.

Australia Group. 2014. *Common Control Lists*. June 15. http://www.australiagroup.net/en/controllists.html

Azim, S. S., et al. 2006. "Studies on Graphite Based Conductive Paint Coatings." *Progress in Organic Coatings* 55(1): 1-4.

Bai, C. 2005. "Ascent of nanoscience in China." *Science Magazine*.

Bank, World. 2012. Knowledge Assessment Methodology.

Barnett, Michael, and Martha Finnemore. 2004. *Rules for the World: International Organizations in Global Politics*. Ithaca, NY: Cornell University Press.

Bartholomew, S. 1997. "National Systems of Biotechnology Innovation: Complex Interdependence in the Global System." *Journal of International Business Studies* 28 (2):241-266.

Battelle. 2012. "2013 Global R&D Funding Forecast." http://battelle.org/docs/r-d-funding-forecast/2013_r_d_funding_forecast.pdf?sfvrsn=0.

Battelle. 2013. "2014 Global R&D Funding Forecast." Accessed 2014-01-25. http://www.battelle.org/docs/tpp/2014_global_rd_funding_forecast.pdf?sfvrsn=4.

Bernstein, AH, and M Libicki. 1998. "High-Tech: The Future Face of War? A Debate." *Commentary* 105:28-31.

BMBF. 2007. Nano-Initiative: Action Plan 2010

Brezis, Elise S., Paul R. Krugman, and Daniel Tsiddon. 1993. "Leapfrogging in International Competition: A Theory of Cycles in National Technological Leadership." *The American Economic Review* 83 (5):1211-1219.

Brooks, Sarah M. 2005a. "Interdependent and Domestic Foundations of Policy Change: The Diffusion of Pension Privatization Around the World." *International Studies Quarterly* 49 (2):273-294.

Brooks, Stephen G. 2005b. *Producing security : multinational corporations, globalization, and the changing calculus of conflict*. Princeton, N.J.: Princeton, N.J. : Princeton University Press.

Büthe, Tim and Walter Mattli. 2011. *The New Global Rulers: The Privatization of Regulation in the World Economy*. Princeton: Princeton University Press.

Caijing. 2013. "Nano is Coming, Finding the Right Path First (in Chinese)." *Caijing Magazine*. Accessed November 2, 2013. http://magazine.caijing.com.cn/2013-06-16/112912273.html.

Cerny, Philip. 1995. "Globalization and the Changing Logic of Collective Action." *International Organization* 49 (4):595-625.

Chandler, A.D. 1977. *The Visible Hand: The Managerial Revolution in American Business*. Cambridge, MA: Belknap Press.

Chang, Kenneth. 2005. "Tiny is Beautiful: Translating 'Nano' into Potential." *The New York Times*, February 22. http://www.nytimes.com/2005/02/22/science/22nano.html?_r=0 2014-04-30.

Chaudhry, Kiren Aziz. 1997. *The price of wealth : economies and institutions in the Middle East*, *Cornell studies in political economy*. Ithaca: Cornell University Press.

Christensen, Clayton. 1997. *The innovator's dilemma : when new technologies cause great firms to fail*. Boston Mass.: Harvard Business School Press.

Christensen, Clayton M. 2006. "The Ongoing Process of Building a Theory of Disruption.(Dialogue on the Effects of Disruptive Technology on Firms and Industries)." *Journal of Product Innovation Management* 23 (1):39.

Cientifica. 2011. Global Funding of Nanotechnologies and Its Impact.

Clunan, Anne L. 2008. "Building Information Networks for Biosecurity." In *Terrorism, War or Disease? Unraveling the Use of Biological Weapons,* pp. 293-310, Anne L. Clunan, Peter R. Lavoy and Susan B. Martin, editors. Palo Alto: Stanford University Press.

Commission, European. 2011. EU Recommendation 2011/696/EU of 18 October 2011 on the Definition of Nanomaterial.

Cornish, P. 2013. *Strategic Cultures in Europe: Security and Defence Policies Across the Continent*, edited by H. Biehl, B. Giegerich and A. Jonas. Springer.

Council, National Research. 2005. Globalization of Materials R&D: Time for a National Strategy. Washington, DC.

Council, National Research. 2013. "Triennial Review of the National Nanotechnology Initiative." National Academy Press. http://www.nap.edu/download.php?record_id=18271.

Council, National Intelligence. 2008. Disruptive Civil Technologies: Six Technologies with Potential Impacts on US Interests out to 2025. In *Report CR 2008-07*: National Intelligence Council.

CSIS. 2012. European Defense Trends 2012: Budgets, Regulatory Frameworks, and the Industrial Base. edited by D. Berteau, G. Ben-Ari, R. Crotty, J. Hofbauer, P. Hermann and S. Raghavan.

Cíentifica. 2013. Half Way to the Trillion Dollar Market? A Critical Review of the Diffusion of Nanotechnologies, Market Report. Research Policy.

Daily, China. 2013. "China has become a global nanotechnology leader, says the CAS President Bai Chunli (in Chinese)." *China Daily*. Accessed November 2, 2013. http://www.chinadaily.com.cn/hqgj/jryw/2013-09-05/content10047265.html.

Daily, Science. 2006. "Joint Lab for Biological Effect for Nanomaterials and Nanosafety is established (in Chinese)." *Science Daily*. Accessed November 2, 2013. http://www.ihep.ac.cn/media/06/060626.htm.

Danneels, Erwin. 2004. "Disruptive Technology Reconsidered." *The Journal of Product innovation management* 21 (1):246-258.

Davis, Carolyn R., Stanley Goos, and Anne M. Schneiderman. 2013. "Ninth Circuit Vacates EPA's Approval of Nanosilver-based Pesticide." Lexology.com. November 26. http://www.lexology.com/library/detail.aspx?g=c76d0d1b-9f49-4b62-b5ca-37268892ad43

Dosi, G., K. Pavitt, and L. Soete. 1990. *The Economics of Technical Change and International Trade*. London, UK: Harvester Wheatsheaf.

Dosi, Giovanni. 1988. "Sources, Procedures, and Microeconomic Effects of Innovation." *Journal of Economic Literature* 26 (3):1120-1171.

DRDO. 2012. "Nanotechnology Applications for Defence Applications," *DRDO Newsletter* 32:11 (November) http://www.drdo.gov.in/drdo/pub/nl/2012/NL_November_2012_web.pdf.

Dunning, John H., and Sarianna M. Lundan. 2009. "The internationalization of corporate R&D: a review of the evidence and some policy implications for home countries." *The Review of Policy Research* 26 (1 2):13.

EDA. 2008. "European Defence Agency News: EDA Establishes New Joint R&T Programme on Disruptive Defence Technologies.". https://http://www.eda.europa.eu/info-hub/news/2008/05/25/EDAEstablishesNewJointRTProgrammeonDisruptiveDefenceTechnologies.

EDA. 2012. "European Defence Agency News: Nanoelectronics' Importance for Defence." https://http://www.eda.europa.eu/info-hub/news/2012/11/13/nanoelectronics-importance-for-defence.

Eden, Lynn. 2004. *Whole World on Fire: Organizations, Knowledge, and Nuclear Weapons Devastation*. Ithaca, NY: Cornell University Press.

Eisler, Matthew N. 2010. "Department of Energy." In *Encyclopedia of Nanoscience and* Society, edited by David H. Guston. Thousand Oaks, CA: Sage.

Elkins, Zachary, Andrew T. Guzman, and Beth A. Simmons. 2006. "Competing for Capital: The Diffusion of Bilateral Investment Treaties, 1960–2000." doi: doi:10.1017/S0020818306060279.

European Commission. 2004. Towards a European Strategy for Nanotechnology; Communication from the Commission. Brussels, Belgium: Commission of the European Communities.

Falkner, Robert and Nico Jaspers. 2012. "Regulating Nanotechnologies: Risk, Uncertainty and the Global Governance Gap." *Global Environmental Politics* 12(1): 30-55.

Fan, C., and L. Li. 2009. "Research on coverage of domestic mainstream media on new and emerging technology: in the case of GMO and Nanotechnology (in Chinese)." 5th Chinese Science and Technology Policy and Management Annual Conference.

Feder, Barnaby J. 2003. "Frontier of Military Technology is in the Size of a Molecule." *New York Times*, April 10.

Feynman, R.P. 1992. "There's plenty of room at the bottom (data storage)." *Journal of Microelectromechanical Systems* 1 (1):60–66.

Finnemore, Martha. 1996. *National Interests in International Society*. Ithaca, NY: Cornell University Press.

Fitzgerald, David. 2014. "Leaving the Back Door Open: How Export Control Reform's Deregulation May Harm American Security," *North Carolina Journal of Law and Technology* 15, Online Edition: 65-99.
Fiorino, Daniel J. 2010. *Voluntary Initiatives, Regulation, and Nanotechnology Oversight: Charting a Path*, Project on Emerging Nanotechnologies.
Florida, Richard. 2005. "The world is spiky: globalization has changed the economic playing field, but hasn't leveled it." *The Atlantic* 296 (3).
Forum, World Economic. 2013. Global Competitiveness Index 2013.
Freeman, C. 1997. "The National System of Innovation in Historical Perspective." In *Technology, Globalization, and Economic Performance*, edited by D. Archibuigi and J. Michie. Cambridge, MA: Cambridge University Press.
Gilpin, Robert. 1981. *War and change in world politics*. Cambridge ; New York : Cambridge University Press.
Gilpin, Robert. 2001. *Global Political Economy*. Princeton: Princeton University Press.
Group, ETC. 2010. Geopiracy: The Case Against Geoengineering.
Heller, Jacob and Christine Peterson. 2007. "Nanotechnology: Maximizing Benefits, Minimizing Downsides." In *Nanoscale: Issues and Perspectives for the Nano Century,* pp. 83-96. edited by Nigel M. de S. Cameron and M. Ellen Mitchell. Hoboken, NJ: Wiley & Sons.
Hindu, The. 2005. "India becoming a Pioneer in Nano Technology." *The Hindu*. http://www.hindu.com/2005/03/25/stories/2005032518320300.htm.
Hollingsworth, J.R., and R. Boyer. 1997. *Contemporary Capitalism: The Embeddedness of Institutions*. Cambridge, MA: Cambridge University Press.
Howard, Sean. 2002. "Nanotechnology and Mass Destruction: The Need for an Inner Space Treaty," *Disarmament Diplomacy* 65 (July-Auugst).
Hsueh, Roselyn. 2011. *China's regulatory state : a new strategy for globalization*, *Cornell studies in political economy*. Ithaca: Cornell University Press.
Hsueh, Roselyn. 2012. "China and India in the Age of Globalization: Sectoral Variation in Postliberalization Reregulation." *Comparative Political Studies* 45 (1):32-61. doi: 10.1177/0010414011421305.
Hu, M. 2012. "Nanotechnology development in Mainland China." IEEE Conference on Technology and Society in Asia.
Huang, Y. 2008. *Capitalism with Chinese characteristics : entrepreneurship and the state*. Cambridge, UK: Cambridge University Press.
Hughes, James, Gwendolyn Sasse, and Claire Gordan. 2004. *Europeanization and Regionalization in the EU's Enlargement to Central and Eastern Europe: The Myth of Conditionality*. London: Palgrave Macmillan.
Hwang, D. 2010. "Ranking the nations on nanotech." *Solid State Technology*.
IAEA. 1992. Guidelines for Transfers of Nuclear-Related Dual-Use Equipment, Material and Related Technology. INFCIRC/254/Rev.1/Part 2 Annex July. http://www.iaea.org/Publications/Documents/Infcircs/Others/infcirc254r1p2.pdf
Initiative, National Nanotechnology. "Manufacturing at the Nanoscale." Accessed December 20, 2013. http://www.nano.gov/nanotech-101/what/manufacturing.
Initiative, National Nanotechnology. "NNI Accomplishments at the Nanoscale." Accessed May 20, 2012. http://www.nano.gov/ nanotechnology-initiatives/nano-achievements.
ISO. 2011. "Nanotechnologies Vocabulary Part 5: Nano/bio interface." https://http://www.iso.org/obp/ui/ - iso:std:iso:ts:80004:-5:ed-1:v1:en:term:2.4 2014-04-28.

Jarvis, D., and N. Richmond. 2011. "Regulation and Governance of Nanotechnology in China: Regulatory Challenges and Effectiveness." *European Journal of Law and Technology* 2 (3):1-11.

Jeremiah, David. 1995. "Nanotechnology and Global Security." (Palo Alto, CA; Fourth Foresight Conference on Molecular Nanotechnology), November 9.

Johnson, Chalmers, Laura D'Andrea Tyson, John Zysman, and Berkeley Roundtable on the International Economy. 1989. *Politics and productivity : the real story of why Japan works*. Cambridge, Mass.: Ballinger.

Jones, Angela, Jeanne Nye and Andrew Greenberg. 2011. "Nanotechnology in the Military: National Defense, Homeland Security." Presentation prepared as part of the *Small Science, Big Decisions* project, University of Wisconsin, Madison Institute for Chemical Education. March. http://ice.chem.wisc.edu/NanoDecisions/PDF/Military.pdf

Jordan, C., N. Kaiser, and V. Moore. 2012. Nanotechnology Patent Survey: Who Will Be the Leaders in the Fifth Technology Revolution? *Nanotechnology Law & Business* 9 (Fall): 122-132.

Juma, C., and L. Yee-Cheong. 2005. Innovation: Applying knowledge in development.: UN Millennium Project Task force on Science, Technology and Innovation.

Juma, Calestous, Lee Yee-Cheong, Technology and Innovation Un Millennium Project. Task Force on Science, and Programme United Nations Development. 2005. *Innovation : applying knowledge in development*. Edited by Calestous Juma, Lee Yee-Cheong, Technology and Innovation Un Millennium Project. Task Force on Science and Programme United Nations Development, *Applying knowledge in development*. London ; Sterling, Va.: London ; Sterling, Va.: Earthscan.

Junk, J., and C. Daase. 2013. "Strategic Cultures in Europe: Security and Defence Policies Across the Continent." In, edited by H. Biehl, B. Giegerich and A. Jonas. Springer.

Kalam, A.P.J. Abdul. 2009. "Dimensions of Nano Science and Technology," Special Address at Nanotechnology Workshop, University of Hyderabad, November 14.

Kay, Luciano, and Philip Shapira. 2011. "The Case of Brazil." In *Nanotechnology and the Challenges of Equity, Equality and Development*, edited by Susan E. Cozzens and Jameson Wetmore. Springer.

Khushf, George. 2004. "The Ethics of Nanotechnology. Vision and Values for a New Generation of Science and Engineering." In *Emerging Technologies and Ethical Issues in Engineering: Papers from a Workshop, October 14-15, 2003*, pp. 29-56, National Academy of Engineering, editor. The National Academies Press.

Klochikihin, Evegeny A. 2011. "Public policy instruments in (re)building national innovation capabilities: cases of nanotechnology development in China, Russia and Brazil " Atlanta Conference on Science and Innovation Policy, Atlanta, GA.

Klochikhin, Evgeny A. 2013."Innovation System in Transition: Opportunities for Policy Learning between China and Russia," *Science and Public Policy* 40, pp. 657-673.

Knell, M. 2011. "Nanotechnology and the Sixth Technological Revolution." In *Nanotechnology and the Challenges of Equity, Equality, and Development*, edited by SE. Cozzens and JM Wetmore. Springer.

Kosal, Margaret E. 2009. *Nanotechnology for chemical and biological defense*. New York:: Springer.

Kosal, Margaret E. 2010. "The security implications of nanotechnology." *Bulletin of the Atomic Scientists* 66 (4):58-69. doi: 10.2968/066004006.

Kosal, Margaret E. 2012. "Nanotechnology Threat Anticipation," unpublished presentation, September 3. Copy on file with authors.

Kosal, Margaret E. 2013. "Strategy, Technology, and Governance: Shift of Responsibility from Nation-states to Individuals." Presentation prepared for delivery at the Society for the Study

of Nanoscience and Emerging Technologies 5th Annual Meeting, October 27-29, Boston, Mass.

Kostoff, R, R. Boylan, and G. Simons. 2004. "Disruptive Technology Roadmaps." *Technological Forecasting and Social Change* 71 (1-2):141–159. doi: 10.1016/S0040-1625(03)00048-9.

Krause, Keith. 1995. *Arms and the State*. Cambridge, MA: Cambridge University Press.

Krugman, Paul. 1986. Pricing to Market when the Exchange Rate Changes. In *NBER Working Papers*: National Bureau of Economic Research, Inc.

Krugman, Paul. 1991. "Increasing Returns and Economic Geography." *Journal of Political Economy* 99 (3):483.

Lehman, Ronald F. 2014. "Unclear and Present Danger: The Strategic Implications of Latent, Dual-Use Science and Technology." In *Strategic Latency and World Power: How Technology Is Changing Our Concepts of Security,* Zachary Davis, Ronald F. Lehman, and Michael Nacht, editors. Livermore, CA: Lawrence Livermore National Laboratory.

Leung, R. 2008. "Doing Nanotechnology in China." Doctor of Philosophy Degree in Sociology, Sociology Department, University of Wisconsin-Madison.

Li, X., Y. Lin, H. Chen, and M. Roco. 2007. "Worldwide Nanotechnology Development: A Comparative Study of USPTO, EPO, and JPO Patents (1976–2004)." *Journal of Nanoparticle Research* 9:977–1002.

Mackenzie, Donald. 1990. *Inventing Accuracy: A Historical Sociology of Nuclear Missile Guidance*. Cambridge, MA: MIT Press.

Maclurcan, Donald. 2005. "Nanotechnology and Developing Countries - Part 2: What Realities?" *AzONano-Online Journal of Nanotechnology* 1.

Magee, Joe C., and Adam D. Galinsky. 2008. "Social Hierarchy: The Self-Reinforcing Nature of Power and Status." *The Academy of Management Annals* 2 (1):351-398.

Mahnken, Thomas G. 2010. *Technology and the American way of war since 1945*. Edited by Inc ebrary. New York ; Chichester, UK: New York ; Chichester, UK : Columbia University Press.

Mangematin, V., K. Errabi, and C. Gauthier. 2011. "Large Players in the Nanogame: Dedicated Nanotech Subsidiaries or Distributed Nanotech Capabilities?" *Journal of Technology Transfer* 36:640–664.

Martins, Paulo Roberto. 2013. "Science for Production x Science for Impacts: Brazilian Development of Nanotechnology in Section XXI." Presentation prepared for delivery at the Society for the Study of Nanoscience and Emerging Technologies 5th Annual Meeting, October 27-29, Boston, Mass.

Maurer, Stephen M., editor. 2009. *WMD Terrorism: Science and Policy Choices*. Cambridge, Mass: MIT Press, 2009.

Maurer, Stephen M. 2010. "Five Easy Pieces: Case Studies of Entrepreneurs Who Organized Private Communities for a Public Purpose" (November 1). Goldman School of Public Policy Working Paper No. GSPP10-011. http://dx.doi.org/10.2139/ssrn.1713329.

Meyer, John W., John Boli, George Thomas, and Francisco O. Ramirez. 1997. "World Society and the Nation-State." *American Journal of Sociology* 103 (1):144-181.

Meyer, John W., and Brian Rowan. 1977. "Institutionalized Organizations: Formal Structures as Myth and Ceremony." *American Journal of Sociology* 83 (2):340-363.

Miyazaki, K., and N. Islam. 2007. "Nanotechnology Systems of innovation—An Analysis of Industry and Academia Research Activities." *Technovation* 27 (11):661–675.

Mori, Yasutaka, Takeshi Ono, Yasushi Miyahira, Vinh Quang Nguyen, Takemi Matsui, and Masayuki Ishihara. 2013. "Antiviral activity of silver nanoparticle/chitosan composites against H1N1 influenza A virus." *Nanoscale Research Letters* 8 (93).

MOST. 2001. "National Nanotechnology Development Strategy (in Chinese)." *MOST*. Accessed November 2, 2013. http://www.most.gov.cn/fggw/zfwj/zfwj2001/200512/t2005121455037.htm.
Mérand, Frédéric. 2008. *European Defence Policy: Beyond the Nation State*: Oxford University Press.
Nano.gov. "One nanometer is a billionth of a meter, or 10-9 of a meter." Accessed 02-28-2014. http://www.nano.gov/nanotech-101/what/definition.
Nanotechnologies, The Project on Emerging. "Inventories." Accessed May 20, 2012. http://www.nanotechproject.org/inventories.
Nanowerk. 2013. "Definition of the Term Nanotechnology." Accessed June 06, 2013. http://www.nanowerk.com/spotlight/spotid=30804.php 2014-05-01.
NATO. 2005. Committee Reports Annual Session 179 STCMT 05 E - The Security Implications of Nanotechnology.
Naughton, B. 1995. *Growing out of the plan : Chinese economic reform, 1978-1993*. Cambridge, UK: Cambridge University Press.
Nazrul, I., and K. Miyazaki. 2010. "An Empirical Analysis of Nanotechnology Research Domains." *Technovation* 30 (4):229–237.
NCNST. 2013. "Official website of the NCNST (in Chinese)." Accessed November 2, 2013. Retrieved from http://www.nanoctr.cn/.
Nelson, Richard R. 1982. *An evolutionary theory of economic change*. Edited by Sidney G. Winter, *Economic change*. Cambridge, Mass.: Cambridge, Mass. : Belknap Press of Harvard University Press.
NERCN. 2013. "Official website of the NERCN (in Chinese)." Accessed November 2, 2013. http://www.nercn.com.cn/content.aspx?classId=10.
NNI. 2014. "Frequently Asked Questions." U.S. National Nanotechnology Initiative (NNI) Accessed March 20, 2014. http://www.nano.gov/nanotech-101/nanotechnology-facts.
NSF. 2012. *Science and Engineering Indicators 2012*.
O'Neill, Kate. 2000a. *Waste trading among rich nations : building a new theory of environmental regulation*. Cambridge, Mass.: Cambridge, Mass. : MIT Press.
O'Neill, Kate. 2000b. *Waste Trading Among Rich Nations: Building a New Theory of Environmental Regulation*. Cambridge, MA: MIT Press.
ObservatoryNANO. 2011. European Nanotechnology Landscape Report.
OECD. 2011. OECD, Science Technology, and Industry Scorecard.
OECD. 2013. Regulatory Frameworks for Nanotechnology in Foods and Medical Products: Summary Results of a Survey Activity. In *OECD Science, Technology and Industry Policy Papers No. 4*. Paris, France: OECD Publishing.
Office, Italian Trade Commission Shanghai. 2009. Market Report on China Biotechnology and Nanotechnology Industries.
O'Neil, Patrick H., Karl Fields, and Don Share. 2010. *Cases in Comparative Politics*. 3rd ed: W.W. Norton.
OPCW. 2012. *Report of the Scientific Advisory Board on Developments in Science and technology for the Third Special Session of the Conference of the States Parties to Review the Operation of the Chemical Weapons Convention*. RC-3/DG.1. October 29.
O'Rourke, E., and M. Morrison. 2012. Challenges for Governments in Evaluating Return on Investment from Nanotechnology and Its Broader Economic Impact. In *OECD Background Paper*, edited by 2012.
Parker, R., and R. Appelbaum. 2012. *Can emerging technologies make a difference in development?* Edited by Rachel A. Parker and Richard P. Appelbaum. New York: New York : Routledge.

Paterson, William E. 2011. The Reluctant Hegemon? Germany Moves Centre Stage in the European Union. Journal of Common Market Studies.

Pavitt, Keith. 1998. "The Social Shaping of the National Science Base." *Research Policy* 27 (8):793–805.

PCAST. 2012. Report to the President and Congress on the Fourth Assessment of the National Nanotechnology Initiative. President's Council of Advisors on Science and Technology.

Porter, Alan L., Jan Youtie, Philip Shapira, and David J. Schoeneck. 2007. "Refining Search Terms for Nanotechnology." *Journal of Nanoparticle Research* 10 (5):715–728. doi: 10.1007/s11051-007-9266-y.

Porter, M., C. Freeman, S. Nelson, K. Winter, K. Pavitt, G. Dosi, and P. Krugman. 1991. *The Geography of Trade*. Cambridge, MA: MIT Press.

Porter, Michael. 1990. *The Competitive Advantage of Nations*. New York, NY: Free Press.

PRC. The State Council of the People's Republic of China Accessed November 2, 2013. http://www.gov.cn/jrzg/2006-02/09/content183787.htm.

Raje, Jaideep. 2011. Commercialisation of Nanotechnology: Global Overview and European Position. Lux Research.

Roco, Mihail C. 2011a. *Nanotechnology research directions for societal needs in 2020 retrospective and outlook*. Edited by Chad A. Mirkin, Mark C. Hersam and SpringerLink. United States] : Dordrecht ; New York: United States : World Technology Evaluation Center ; Dordrecht ; New York : Springer.

Roco, Mihail C. 2011b. "The long view of nanotechnology development: the National Nanotechnology Initiative at 10 years.(Editorial)(Report)." *Journal of Nanoparticle Research: An Interdisciplinary Forum for Nanoscale Science and Technology* 13 (2):427.

Roco, Mihail C. Bainbridge, William S., Tonn, Bruce, Whitesides, George. 2013. "Convergence of Knowledge, Technology, and Society: Beyond Convergence of Nano-Bio-Info-Cognitive Technologies." World Technology Evaluation Center, Inc. http://www.wtec.org/NBIC2/Docs/FinalReport/Pdf-secured/NBIC2-FinalReport-WEB.pdf.

Rodine-Hardy, Kirsten L. 2010. "Big Government for Small Technology: European Regulation for Nanotechnology." Paper prepared for delivery at the European Consortium of Political Research Conference in Dublin, Ireland June 17 – 21.

Rodine-Hardy, Kirsten. 2013. *Global markets and government regulation in telecommunications*. Cambridge: Cambridge University Press.

Roffey, R. 2013. "Russian Science and Technology is Still Having Problems—Implications for Defense Research." *Journal of Slavic Military Studies* 26 (2):162-188.

Rogers, Everett M. 1995. *Diffusion of Innovations*. 4th ed. New York: Free Press.

Romer, Paul M. 1986. "Increasing returns and long-run growth." *Journal of Political Economy* 94:1002.

Romer, Paul M. 1990. "The origins of endogenous growth. (models for studying growth)." *Journal of Economic Perspectives* 8 (1):3.

Rosecrance, Richard. 1999. *The Rise of the Virtual State*. New York: Basic Books.

Russian Federal Technological and Export Control Service (FSTEC). 2011. *Spisok Tovarov i Tekhnologii Dvoinnovo Naznacheniia, Kotorie Mogut Byt' Ispolsovanyi pri Vooruzhenii i Voennoi Tekhniki i v Otnoshennii Kotoryikh Osushchestvliaetsia Eksportnyi Kontrol* (List of Dual-Use Goods and Technnologies Capable of Use in Weapons and Military Equipment and Subsequently Subject to Export Control). December 17.

Salamanca-Buentello, Fabio, Deepa L. Persad, Erin B. Court, Douglas K. Martin, Abdallah S. Daar, and Peter A. Singer. 2005. "Nanotechnology and the Developing World (Policy Forum)." *PLoS Medicine* 2 (5):e97. doi: 10.1371/journal.pmed.0020097.

Sargent, John F. 2008. *Nanotechnology and U.S. Competitiveness: Issues and Options*. Edited by Service Library Of Congress Washington Dc Congressional Research.

Sargent, John F., Jr. 2010. Nanotechnology: a policy primer.(Congressional Research Service)(Report).

Sargent, John F., Jr. 2012. Nanotechnology: a policy primer.(Company overview).

Saxenian, Annalee. 1994. *Regional Advantage: Culture and Competition in Silicon Valley and Route 128*. Cambridge, MA: Harvard University Press.

SCENIHR. 2006. 3.2. Definitions and Scope: The Appropriateness of Existing Methodologies to Assess the Potential Risks Associated with Engineered and Adventitious Products of Nanotechnologies.

Schmidt, Vivien A. 2006. "Procedural democracy in the EU: the Europeanization of national and sectoral policy-making processes." *Journal of European Public Policy* 13 (5):670-691.

Sciences, Chinese Academy of. "2013." Institutional Repository of Insitute of Mechanics Accessed Accessed November 2, 2013. http://lxyd.imech.ac.cn/info/detail.asp?infono=16874.

Sell, Susan K. 2003. *Private power, public law the globalization of intellectual property rights*. Edited by Inc ebrary. Cambridge, U.K. ; New York: Cambridge, U.K. ; New York : Cambridge University Press.

Shambaugh, D. 2002. *Modernizing China's military progress, problems, and prospects*. Berkeley, CA: University of California Press.

Shapira, Philip, and Jue Wang. 2009. "From Lab to Market? Strategies and Issues in the Commercialization of Nanotechnology in China." *Asian Businesses and Environment* 8 (4):461-489.

Shapira, Philip and Jue Wang. 2010. "Follow the Money," *Nature* 486 (2 December): 627-628.

Shapira, Philip, and Jan Youtie. 2012. The Economic Contributions of Nanotechnology to Green and Sustainable Growth.

Shirk, S. 1993. "The political logic of economic reform in China." In. Berkeley, CA: University of California Press.

Siegel, Jakub, Olexiy Lyutakov, Vladimír Rybka, Zdeňka Kolská, and Václav Švorčík. 2011. Properties of gold nanostructures sputtered on glass. In *Nanoscale Research Letters*.

Singer, P., F. Salamanca-Buentello, and A. Daar. 2005. "Harnessing Nanotechnology to improve global equity: the less industrialized countries are eager to play an early role in developing this technology; the global community should help them." *Issues in Science and Technology* 21 (4).

Singh, J.P. 1999. *Leapfrogging Development: The Political Economy of Telecommunications Restructuring*. Albany, NY: SUNY Press.

Song, Y., X. Li, and X. Du. 2009. "Exposure to nanoparticles is related to pleural effusion, pulmonary fibrosis and granuloma." *European Respiratory Journal* 34 (3):559-567. doi: 10.1183/09031936.00178308.

Speshock, Janice L, Laura K Braydich-Stolle, Eric R Szymanski, and Saber M Hussain. 2011. "Silver and Gold Nanoparticles Alter Cathepsin Activity In vitro." *Nanotscale Research Letters* 6 (17).

Stopford, John M., John S. Henley, and Susan Strange. 1991. *Rival States, Rival Firms: Competition for World Market Shares*: Cambridge University Press.

Strange, Susan. 1996. *The Retreat of the State: The Diffusion of Power in the World Economy*. Cambridge: Cambridge University Press.

Tao, Yu, Yuxiao Tao, Biaobing Wang, Liuyang Wang, and Yanlong Tai. 2013. "A facile approach to a silver conductive ink with high performance for macroelectronics." *Nanoscale Research Letters* 8 (296).

Technology, National Center for Nanoscience and. 2011. Nanotechnology Standard Research result Presented at the 11th Five-Year Plan National Prominent S&T Achievement Exhibition (in Chinese). National Center for Nanoscience and Technology.

Tilly, C., and G. Ardant. 1975. *The Formation of national states in Western Europe*. Princeton, N.J.: Princeton University Press.

Umar, Sirajo, Yuanfeng Liu, Yiguang Wu, Guangtao Li, Jiabo Ding, Runsong Xiong, and Jinchun Chen. 2013. "Highly potent silver-organoalkoxysilane antimicrobial porous nanomembrane." *Nanoscale Research Letters* 8 (164).

UNCTAD. 2005. World Investment Report 2005: Transnational Corporations and the Internationalization of R&D.

U.S. Food and Drug Administration. 2011. "Considering Whether an FDA-Regulated Product Involves the Application of Nanotechnology." http://www.fda.gov/RegulatoryInformation/Guidances/ucm257698.htm

U.S. Department of State. 2014. "Overview of U.S. Export Control System." June 15. http://www.state.gov/strategictrade/overview/

Wallerstein, Immanuel Maurice. 1974. *The modern world-system*. New York: New York : Academic Press.

Wassenaar Arragenment. 2013. *List of Dual-Use Good and Technologies and Munitions List.* April 12. http://www.wassenaar.org/controllists/2013/WA-LIST%20(13)%201/WA-LIST%20(13)%201.pdf

Weintraub, B., Y. G. Wei, and Z. L. Wang. 2009. "Optical Fiber/Nanowire Hybrid Structures for Efficient Three-Dimensional Dye-Sensitized Solar Cells." *Angewandte Chemie*-International Edition 48(47): 8981-8985.

Westerlund, F. 2011. *Russian Nanotechnology R&D: Thinking Big about Small Scale Scie*nce.: Stockholm: Swedish Defense Research Agency.

White, Lynn Townsend. 1964. *Medieval Technology and Social Change*: Oxford University Press.

Woods, Ngaire. 2006. *The Globalizers: The IMF, the World Bank and their Borrowers*. Ithaca, NY: Cornell University Press.

Xinhua. 2001. "President Jiang Zemin Meets with Delegates of 2001 International Nanomaterials Conference (in Chinese).". Accessed November 2, 2013. Retrieved from http://www1.peopledaily.com.cn/GB/paper39/3710/455041.html.

Yang, D. 2010. *Technology of empire: telecommunications and Japanese expansion in Asia, 1883-1945*.

Youtie, J., M. Iacopetta, and S. Graham. 2007. "Assessing the Nature of Nanotechnology: Can We Uncover an Emerging General Purpose Technology?" *The Journal of Technology Transfer* 33 (3):315–329.

Youtie, Jan, Philip Shapira, and Alan L. Porter. 2008. "Nanotechnology publications and citations by leading countries and blocs.(Report)." *Journal of Nanoparticle Research: An Interdisciplinary Forum for Nanoscale Science and Technology* 10 (6):981.

Zheng, Y., and M. Chen. 2006. China plans to build an innovative state. Nottingham, UK: China Policy Institute.

Zysman, John, and Laura D'Andrea Tyson. 1983. *American industry in international competition : government policies and corporate strategies*, *Cornell studies in political economy*. Ithaca: Cornell University Press.