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Economic growth and breakthrough innovations: A case study of nanotechnology

Lisa Larrimore Ouellette

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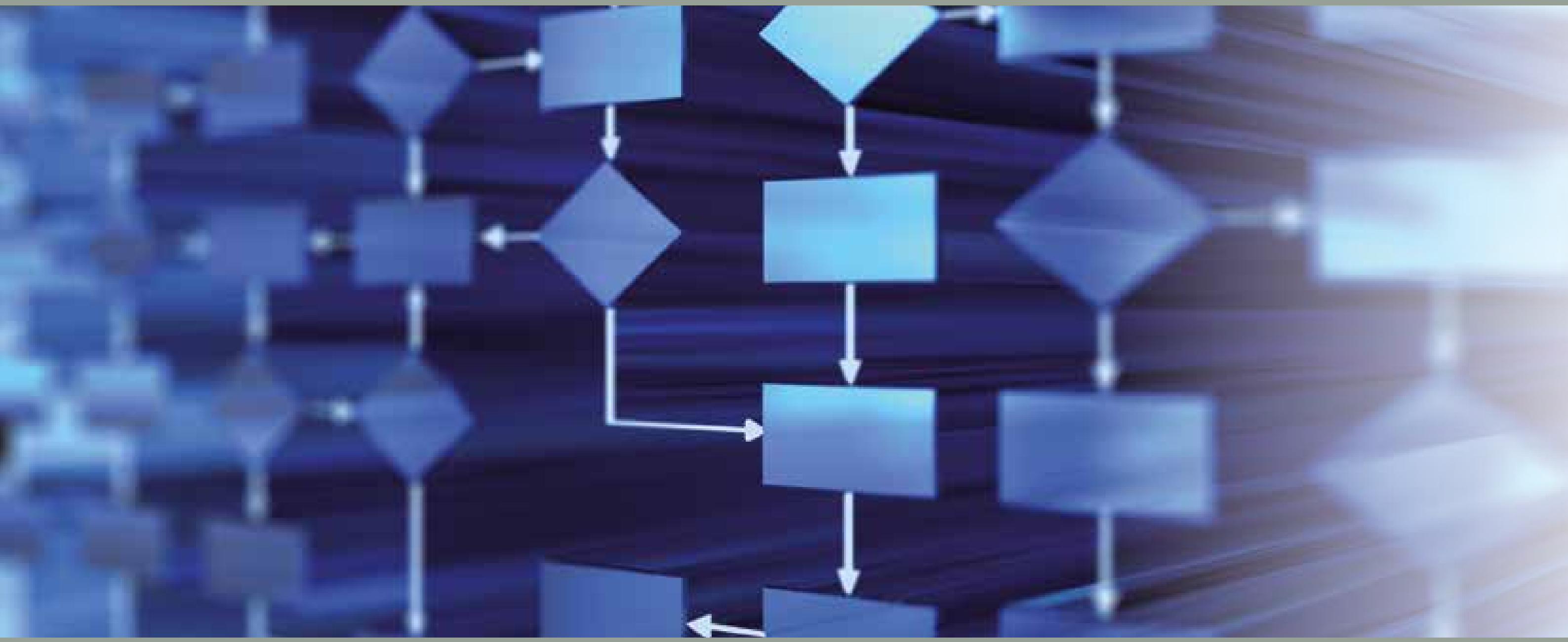

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Economic Growth and Breakthrough Innovations: A Case Study of Nanotechnology

Lisa Larrimore Ouellette[*]

Abstract

This paper examines the role of intellectual property and other innovation incentives in the development of one field of breakthrough innovation: nanotechnology. Because nanotechnology is an enabling technology across a wide range of fields, the nanotechnology innovation ecosystem appears to be a microcosm of the global innovation ecosystem. Part I describes the nature of nanotechnology and its economic contribution, Part II explores the nanotechnology innovation ecosystem, and Part III focuses on the role of IP systems in the development of nanotechnology.

Keywords: Innovation, nanotechnology, intellectual property

JEL Classification: O3, O34, O380

Disclaimer

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[*] Assistant Professor, Stanford Law School, United States of America

I. Nanotechnology's Development and Economic Contribution

Nanotechnology is technology at the nanometer scale—the scale of atoms and molecules. A nanometer is one-billionth of a meter, or the length of about three to twenty atoms. Nanoscale particles are not new, but only in recent decades have scientists been able to truly visualize and control nanoscale phenomena. The vision of the technological promise of manipulating matter at the nanoscale is often attributed to Nobel-Prize-winning physicist Richard Feynman, who famously argued in 1959 that "there is plenty of room at the bottom" for applications such as nanoscale circuits and nanomedicine.[1] Since then, as discussed below, researchers have produced extraordinary breakthroughs in nanoscale science and engineering with widespread applications, although some of the hype (and occasional hysteria) surrounding the technology has abated.

The term "nanotechnology" encompasses a vast range of technological developments. The U.S. Office of Science and Technology Policy broadly defines nanotechnology as any technology involving "the understanding and control of matter at dimensions between approximately 1 and 100 nanometers, where unique phenomena enable novel applications."[2] Most nanotechnology studies adopt a similar definition, although figuring out whether a specific technology falls under this definition can be challenging. The lack of uniform international standards for classifying nanotechnology has complicated efforts to assess nanotechnology's overall impact or to compare analyses by different groups.[3] This paper attempts to synthesize a broad literature on nanotechnology, but the definitional ambiguity remains a necessary caveat.

In the remainder of this Part, Section I.A briefly reviews selected developments in nanotechnology with a focus on nanoelectronics. Section I.B then discusses nanotechnology's transformative potential and attempts to quantify its significant economic contribution.

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[1] Richard Feynman, Professor, Cal. Inst. of Tech., There's Plenty of Room at the Bottom, Address to the American Physical Society (December 29, 1959), *in* ENGINEERING & SCI., Feb. 1960, at 22, *available at* http://calteches.library.caltech.edu/1976/1/1960Bottom.pdf.

[2] SUBCOMMITTEE ON NANOSCALE SCIENCE, ENGINEERING, AND TECHNOLOGY, OFFICE OF SCIENCE AND TECHNOLOGY POLICY, THE NATIONAL NANOTECHNOLOGY INITIATIVE SUPPLEMENT TO THE PRESIDENT'S 2015 BUDGET 3 (2014), *available at* http://www.whitehouse.gov/sites/default/files/microsites/ostp/NNI_FY15_Final.pdf.

[3] *See* ORG. FOR ECON. CO-OPERATION & DEV., SYMPOSIUM ON ASSESSING THE ECONOMIC IMPACT OF NANOTECHNOLOGY: SYNTHESIS REPORT 8 (2013), *available at* http://www.oecd.org/sti/nano/Washington%20Symposium%20Report_final.pdf.

A. Selected Developments in Nanotechnology

Nanotechnology, like most fields of innovation, has depended on prior scientific progress. The technological developments of the late twentieth century would have been impossible without the theoretical breakthroughs of the early twentieth century involving the basic understanding of molecular structure and the laws of quantum mechanics that govern nanoscale interactions.[4] And a complete history of nanotechnology not only would describe all the foundational developments in physics, chemistry, biology, and engineering, but also would extend across a vast range of applications today.[5]

By most accounts, the first consumer nanotechnology products involved passive nanoscale additives that were used to improve the properties of materials such as tennis rackets, eyeglasses, and sunscreen.[6] (Verifying the precise technology behind these claims, however, is often difficult.[7]) Inadvertent use of nanomaterials has an even longer history. Premodern examples include Roman dichroic glass with colloidal gold and silver and Damascus saber blades containing carbon nanotubes, and nanoparticles were often manufactured in bulk by chemical means by the mid-nineteenth century.[8]

The nanotechnology umbrella also covers many developments in biotechnology and medicine. The biomolecular world operates on the nanoscale: DNA has a diameter of about two nanometers, and many proteins are around ten nanometers in size. Scientists have engineered these biomolecules and other nanomaterials for biological diagnostics and therapeutics, such as for targeted drug delivery for cancer treatment.[9] As of 2013, a few hundred nano-related medical therapies had been approved or had entered clinical trials in the United States.[10]

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[4] *See generally* VLADIMIR MITIN ET AL., QUANTUM MECHANICS FOR NANOSTRUCTURES 1-2 (2010).

[5] For a comprehensive discussion, see WORLD TECH. EVALUATION CTR., NANOTECHNOLOGY RESEARCH DIRECTIONS FOR SOCIETAL NEEDS IN 2020 (Mihail C. Roco et al. eds. 2011).

[6] *See, e.g.*, *George A. Kimbrell, Nanomaterial Consumer Products and FDA Regulation: Regulatory Challenges and Necessary Amendments*, 3 NANOTECHNOLOGY L. & BUS. 329, 331 (2006).

[7] *See* Jermey N.A. Matthews, *Taking Stock of the Nanotechnology Consumer Products Market*, 67 PHYSICS TODAY 22 (2014).

[8] *See* MITIN ET AL., *supra* note 4; JEREMY RAMSDEN, NANOTECHNOLOGY 9 (2011); *Nanotechnology Timeline*, NAT'L NANOTECHNOLOGY INITIATIVE, http://nano.gov/timeline (last visited Dec. 1, 2014).

[9] *See, e.g.*, THE NANOBIOTECHNOLOGY HANDBOOK (Yubing Xie ed., 2012); Priyambada Parhi et al., *Nanotechnology-Based Combinational Drug Delivery: An Emerging Approach for Cancer Therapy*, 17 DRUG DISCOVERY TODAY 1044 (2012).

[10] Toni Feder, *US Nano Thrust Tilts Toward Technology Transfer*, PHYSICS TODAY, Sept. 2013, at 21.

In some ways nanotechnology resembles prior "general purpose technologies" that have been at the center of prior periods of rapid development—such as the combustion engine, electricity, and the computer—in that nanotechnology development is occurring across technology spaces.[11] Rather than attempting to describe the full history and breadth of nanotechnology research and development, this paper focuses on three strands of R&D from the perspective of nanoelectronics: (1) electron and scanning probe microscopy, which are essential research tools for understanding and creating nanoscale devices; (2) fullerenes, carbon nanotubes, and graphene, some of the most promising nanoscale materials (although they have seen few commercial applications thus far); and (3) commercial nanoelectronics, from transistors to magnetic memory, which have already had a significant market impact.

1. Research Tools: Electron and Scanning Probe Microscopy

The ability to visualize nanoscale structures has been critical to the development of nanotechnology. Nanoscale features cannot be seen even with the most powerful optical microscopes, since they are smaller than the wavelength of light.[12] But electrons have a much smaller wavelength than visible light—a discovery for which French physicist Louis de Broglie won the 1929 Nobel Prize[13]—and they thus can be used to image much smaller features. Images from the first functional transmission electron microscope (TEM) were published in 1932 by Max Knoll and his PhD student Ernst Ruska at the Technical University of Berlin,[14] for which Ruska later shared the Nobel Prize.[15] The first commercial TEM was built just four years later by Metropolitan-Vikers in the UK, although successful production did not take off until Siemens began producing TEMs in Germany in 1939.[16] Ruska joined Siemens in 1936, where he worked with researchers such as Bodo von Borries to develop their commercial product.[17]

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[11] Stuart J.H. Graham & Maurizio Iacopetta, *Nanotechnology and the Emergence of a General Purpose Technology*, 115/116 ANNALS ECON. & STAT. 5 (2014).

[12] *See* RAMSDEN, *supra* note 8, at 5. Even these limits have recently been questioned, however. The 2014 Kavli Prize in Nanoscience was awarded for advances that have challenged the resolution limits of optical microscopy. *See 2014 Kavli Prize Laureates in Nanoscience*, KAVLI PRIZE (May 29, 2014), http://www.kavliprize.org/prizes-and-laureates/prizes/2014-kavli-prize-laureates-nanoscience.

[13] *The Nobel Prize in Physics 1929*, NOBELPRIZE.ORG, http://www.nobelprize.org/nobel_prizes/physics/laureates/1929 (last visited Dec. 1, 2014).

[14] DAVID B. WILLIAMS & C. BARRY CARTER, THE TRANSMISSION ELECTRON MICROSCOPE 4 (2d ed. 2009).

[15] Press Release, Royal Swedish Acad. of Sci., The Nobel Prize in Physics 1986 (Oct. 15, 1986), *available at* http://www.nobelprize.org/nobel_prizes/physics/laureates/1986/press.html.

[16] *See* WILLIAMS & CARTER, *supra* note 14. Siemens appears to have been working on these devices concurrently with Knoll and Ruska, as Reinhold Rüdenberg at Siemens filed a patent on an electron microscope in 1931. *See* U.S. Patent No. 2,058,914 (filed May 27, 1932) (claiming priority to a German application filed on May 30, 1931).

[17] Dennis McMullan, *The Early Development of the Scanning Electron Microscope*, *in* BIOLOGICAL LOW-VOLTAGE SCANNING ELECTRON MICROSCOPY 1, 3, 9 (Heide Schatten & James B. Pawley eds. 2008); *Ernst Ruska – Biographical*, NOBELPRIZE.ORG, http://www.nobelprize.org/nobel_prizes/physics/laureates/1986/ruska-bio.html (last visited Dec. 1, 2014).

In 1935, Knoll published the first images made by *scanning* an electron beam in a precursor to the scanning electron microscope (SEM).[18] Manfred von Ardenne, working under a contract with Siemens, actually obtained SEM images in 1933, although these appear only in a patent application and were not published.[19] He did, however, publish images with 40-nanometer resolution in 1938 from a related device, the first scanning transmission electron microscope (STEM).[20] A team at RCA in New Jersey worked on scanning electron microscopy around 1938 to 1942, but RCA discontinued the project due to the disappointing quality of the images.[21] In light of this apparent failure, little additional work occurred until Charles Oatley and his engineering PhD students at Cambridge University began researching SEM technology in 1948.[22] In 1962, Oatley convinced the Cambridge Instrument Company to produce a commercial SEM.[23] One of Oatley's graduates joined the company and was instrumental in the commercial product's development,[24] just as Ruska had helped moved TEM technology from academic prototype to commercial production three decades earlier. The Cambridge Instrument Company sold its first commercial SEM in 1965.[25] Six months later the Japanese firm JEOL began marketing a competing product based on the design of an SEM that Oatley's group had sold to the Pulp and Paper Research Institute of Canada in the late 1950s.[26]

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[18] McMullan, *supra* note 17, at 3-4. An earlier description of a microscope with a scanning electron beam can be found in 1929 German patents by Hugo Stinzing of Gissen University, but he did not know how to focus an electron beam, and there is no evidence that he attempted to construct the instrument. *Id.* at 2.

[19] Stephen J. Pennycook, *A Scan Through the History of STEM*, *in* SCANNING TRANSMISSION ELECTRON MICROSCOPY: IMAGING AND ANALYSIS 1, 1 (Stephen J. Pennycook & Peter D. Nellist eds., 2011).

[20] *See* McMullan, *supra* note 17, at 5, 8-10; Pennycook, *supra* note 19, at 1. STEMs and SEMs operate on the same basic principles, but with STEMs thin samples are used and the microscope captures the transmission of electrons through the sample.

[21] *See* McMullan, *supra* note 17, at 5-6.

[22] *See id.* at 12; Oliver C. Wells & David C. Joy, *The Early History and Future of SEM*, 38 SURFACE & INTERFACE ANALYSIS 1738 (2006).

[23] *See* McMullan, *supra* note 17, at 20.

[24] *See id.*

[25] *See id.* at 1, 20.

[26] *See id.* at 20-21 (describing the sale to the Canadian firm and the introduction of JEOL's product); Wells & Joy, *supra* note 22, at 1739 (reporting that the SEM sold to Canada was the basis for JEOL's product).

STEM technology was slower to progress: after von Ardenne's STEM was destroyed in 1944 in a WWII air raid on Berlin, a STEM was not developed again for over two decades until Albert Crewe created one at the University of Chicago.[27] In 1970, Crewe reported the first observations of single atoms using an electron microscope.[28] (Collaborators of Crewe's later translated STEM improvements such as ultra-high vacuum to SEM technology in 1974.[29]) The first commercial STEM was introduced by the British firm VG Microscopes.[30] After VG Microscopes ceased production in 1996, a professor at the University of Illinois who wanted to buy a dedicated STEM worked with JEOL to convert one of their microscopes into an STEM with atomic-resolution capacity.[31] As more manufacturers entered the market, the number of atomic-resolution STEMs doubled within a few years.[32] Today, most TEM and STEM instruments are capable of a spatial resolution approaching 0.13 nanometers for thin samples.[33]

A different technique for imaging nanoscale surfaces is scanning probe microscopy, which involves measuring the interaction between a surface and an extremely fine probe that is scanned over it, resulting in three-dimensional images of the surface. The first scanning tunneling microscope (STM) was developed in 1981 at IBM in Zurich by Gerd Binnig and Heinrich Rohrer, for which they shared the 1986 Nobel Prize in Physics (along with Ernst Ruska for his creation of the first electron microscope).[34] Don Eigler, an IBM researcher in California, used an STM in 1989 not just to image but to *manipulate* individual Xenon atoms (to spell out "IBM"), for which he shared the 2010 Kavli Prize in Nanoscience.[35] While Binnig was on leave at Stanford in 1985, he invented a different type of scanning probe microscope—the atomic force microscope (AFM)—which he produced with colleagues from Stanford and IBM.[36] With the AFM it became possible to image materials that were not electrically conductive. IBM holds the basic patents on both the STM and the AFM.[37] Both instruments are now routine tools for investigating nanoscale materials with atomic resolution.[38]

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[27] *See* Pennycook, *supra* note 19, at 3, 6-7.

[28] *See id.* at 7.

[29] *See* McMullan, *supra* note 17, at 22.

[30] Pennycook, *supra* note 19, at 36.

[31] *See id.* at 40.

[32] *See id.*

[33] WORLD TECH. EVALUATION CTR., *supra* note 5, at 77.

[34] Press Release, Royal Swedish Acad. of Sci., *supra* note 15.

[35] *2010 Kavli Prize Laureates in Nanoscience*, KAVLI PRIZE (June 3, 2010), http://www.kavliprize.org/prizes-and-laureates/prizes/2010-kavli-prize-laureates-nanoscience.

[36] G. Binnig et al., *Atomic Force Microscope*, 56 PHYSICAL REV. LETTERS 930 (1986).

[37] *See* U.S. Patent No. 4,724,318 (filed Aug. 4, 1986, priority date Nov. 26, 1985) ("Atomic force microscope and method for imaging surfaces with atomic resolution"); U.S. Patent No. 4,343,993 (filed Sept. 12, 1980, priority date Sept. 20, 1979) ("Scanning tunneling microscope"). Each of these patents has counterparts in other countries.

[38] *See* WORLD TECH. EVALUATION CTR., *supra* note 5, at 73.

2. Promising Nanomaterials: Fullerenes, Nanotubes, and Graphene

Some of the most promising nanomaterials are structures in which carbon atoms are arranged primarily in hexagons, including soccer-ball-like structures known as fullerenes, cylinders known as carbon nanotubes, and sheets known as graphene. This section briefly reviews the growth of work with these materials. All of these discoveries rested on pioneering theoretical work about the behavior of electronics in carbon, such as the work in the 1960s through 1980s for which MIT physics professor Mildred S. Dresselhaus received the 2012 Kavli Prize in Nanoscience.[39]

Fullerenes were discovered in 1985 at Rice University by Robert Curl, Harold Kroto, and Richard Smalley, for which they were awarded the 1996 Nobel Prize in Chemistry.[40] Their research was supported by grants from federal agencies in the United States (the Army Research Office, the National Science Foundation, and the Department of Energy) and by the Welch Foundation, a nonprofit funder of basic chemical research.[41] In 1990, physicists at the Max Planck Institute for Nuclear Physics and at the University of Arizona discovered a method of producing fullerenes in larger quantities.[42] This advance led to an explosion in fullerene-related patenting by entities that now saw commercially viable opportunities, including academic researchers such as Richard Smalley[43] and corporations such as Sanofi-Aventis.[44] Fullerenes have been used commercially to enhance products such as badminton rackets and cosmetics, but their most promising applications are for organic electronics and bioscience.[45]

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[39] *2012 Kavli Prize Laureates in Nanoscience*, KAVLI PRIZE (May 31, 2012), http://www.kavliprize.org/prizes-and-laureates/prizes/2012-kavli-prize-laureates-nanoscience.

[40] *The Nobel Prize in Chemistry 1996*, NOBELPRIZE.ORG (Oct. 9, 1996), http://www.nobelprize.org/nobel_prizes/chemistry/laureates/1996/press.html.

[41] H.W. Kroto et al, *C_{60}: Buckminsterfullerene*, 318 NATURE 162, 163 (1985).

[42] W. Krätschmer et al., *Solid C_{60}: A New Form of Carbon*, 347 NATURE 354 (1990).

[43] *E.g.*, U.S. Patent No. 5,591,312 (filed May 15, 1995); U.S. Patent No. 5,556,517 (filed June 7, 1995); U.S. Patent No. 5,300,203 (filed Nov. 27, 1991); U.S. Patent No. 5,227,038 (filed Oct. 4, 1991).

[44] *See* Richard Michalitsch et al., *The Fullerene Patent Landscape in Europe*, 5 NANOTECHNOLOGY L. & BUS. 85, 86, 92 (2008).

[45] *See* Michael D. Diener, *Fullerenes for Photovoltaic and Bioscience Applications*, SIGMA-ALDRICH, http://www.sigmaaldrich.com/materials-science/nanomaterials/fullerenes.html (last visited Jan. 30, 2015).

The discovery of carbon nanotubes is often attributed to the Japanese academic physicist Sumio Iijima in 1991, although the Soviet scientists L.V. Radushkevich and V.M. Lukyanovich published a TEM image of a 50-nanometer-diameter carbon nanotube in 1952, and nanotubes were rediscovered a number of times since then.[46] The formation of *single-walled* carbon nanotubes—i.e., cylinders with walls made from a single atomic layer of carbon—was simultaneously reported in 1993 by Iijima and Ichihashi of NEC Corporation in Japan[47] and by Bethune et al. of IBM in California.[48] Since then, there has been an explosion of interest in nanotubes.[49] From 2001 to 2010 the U.S. National Science Foundation awarded 1,142 grants related to carbon nanotubes, with an average award amount of $338,398, making nanotubes the second most heavily funded nanotechnology topic after thin films.[50] Like carbon fullerenes, dispersed carbon nanotubes are already used in diverse commercial products, including thin-film electronics.[51] But the most promising applications—those that take advantage of the electrical properties of individual nanotubes—are still many steps away from the commercial stage.[52]

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[46] *See* Marc Monthioux & Vladimir L. Kuznetsov, *Who Should Be Given the Credit for the Discovery of Carbon Nanotubes?*, 44 CARBON 1621 (2006).

[47] Sumio Iijima & Toshinari Ichihashi, *Single-Shell Carbon Nanotubes of 1-nm Diameter*, 363 NATURE 603 (1993). Iijima was one of the recipients of the 2008 Kavli Prize in Nanoscience for his work on carbon nanotubes. *See 2008 Kavli Prize Laureates in Nanoscience*, KAVLI PRIZE (Apr. 16, 2014), http://www.kavliprize.org/prizes-and-laureates/prizes/2008-kavli-prize-laureates-nanoscience.

[48] D.S. Bethune et al., *Cobalt-Catalysed Growth of Carbon Nanotubes with Single-Atomic-Layer Walls*, 363 NATURE 605 (1993).

[49] For an overview of carbon nanotube patenting, see John C. Miller & Drew L. Harris, *The Carbon Nanotube Patent Landscape*, 3 NANOTECHNOLOGY L. & BUS. 427 (2006).

[50] *See* Hsinchun Chen et al., *Global Nanotechnology Development from 1991 to 2012: Patents, Scientific Publications, and Effect of NSF Funding*, 15 J. NANOPARTICLE RES. 1951, p.15 tbl.12 (2013).

[51] Michael F.L. De Volder et al., *Carbon Nanotubes: Present and Future Commercial Applications*, 339 SCIENCE 535 (2013).

[52] *See id.*

Graphene, the newest carbon-based nanomaterial of interest, was described theoretically in 1947 by P.R. Wallace,[53] but its physical isolation was not described until 2004, when Andre Geim, Konstantin Novoselov, and colleagues at the University of Manchester showed that they could use Scotch tape to extract individual graphene sheets from graphite crystals.[54] In 2005, they published electrical measurements on a single graphene layer,[55] and in 2010, Geim and Novoselov won the Nobel Prize for their graphene work.[56] Unlike the Smalley group at Rice, the Geim group at Manchester has shown little interest in patenting their discoveries.[57] But the overall patent landscape shows an explosion of interest in the material. The U.K. Intellectual Property Office (IPO) counted 8,416 published patent applications related to graphene as of February 2013, with the largest patent families coming from Korean and Chinese corporations and universities.[58] It is likely, however, that many of these patents are speculative. Graphene has potential applications ranging from electronics to biosensing,[59] but significant hurdles remain to implementation.[60] For example, a recent review in *Science* concluded that integrating graphene into solar cells and batteries holds promise for improved energy conversion and storage, but that "further improvement of high-volume manufacturing and transfer processes ...is needed."[61]

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[53] P.R. Wallace, *The Band Structure of Graphite*, 71 PHYSICAL REVIEW 622 (1947).

[54] K.S. Novoselov et al., *Electric Field Effect in Atomically Thin Carbon Films*, 306 SCIENCE 666 (2004). For a description of the "eureka moment" in 2002 that led to this publication, see John Colapinto, *Material Question: Graphene May Be the Most Remarkable Substance Ever Discovered. But What's It For?*, NEW YORKER, Dec. 22, 2014, *available at* http://www.newyorker.com/magazine/2014/12/22/material-question.

[55] K.S. Novoselov et al., *Two-Dimensional Atomic Crystals*, 102 PROC. NAT'L ACADEMY SCI. 10451 (2005).

[56] *See* ROYAL SWEDISH ACAD. OF SCIS., SCIENTIFIC BACKGROUND ON THE NOBEL PRIZE IN PHYSICS 2010: GRAPHENE (2010), *available at* http://www.nobelprize.org/nobel_prizes/physics/laureates/2010/advanced-physicsprize2010.pdf.

[57] *See* Quentin Tannock, *Exploiting Carbon Flatland*, 11 NATURE MATERIALS 2 (2012).

[58] UNITED KINGDOM INTELLECTUAL PROPERTY OFFICE, GRAPHENE: THE WORLDWIDE PATENT LANDSCAPE IN 2013, at 2-4 (2013), *available at* https://www.gov.uk/government/publications/graphene. For another look at the graphene patent landscape, see Chinh H. Pham & Roman Fayerberg, *Current Trends in Patenting Graphene and Graphene-Based Inventions*, 8 NANOTECHNOLOGY L. & BUS. 10 (2011).

[59] *See generally* GRAPHENE: SYNTHESIS, PROPERTIES, AND PHENOMENA (C.N.R. Rao & A.K. Sood eds., 2013); LUIS E.F. FOA TORRES ET AL., INTRODUCTION TO GRAPHENE-BASED NANOMATERIALS (2014).

[60] *See* Colapinto, *supra* note 54.

[61] Francesco Bonaccorso et al., *Graphene, Related Two-Dimensional Crystals, and Hybrid Systems for Energy Conversion and Storage*, 347 SCIENCE 41, 41 (2015).

3. Commercial Nanoelectronics

Although many of the much-touted potential applications of carbon-based nanomaterials remain speculative, other nanotechnology developments have already had a significant market impact. Nanotechnology has led to significant improvements in commercial electronics, including improved transistors and magnetic memory. For example, as of 2010, about sixty percent of the U.S. semiconductor market involved nanoscale features, for a market value of about $90 billion.[62]

This steady shrinking of device size is a result of the persistence of "Moore's Law," which describes the doubling of the number of transistors on a chip every eighteen to twenty-four months.[63] To shrink devices below 100 nanometers, researchers had to overcome significant challenges. For example, new materials were developed to provide necessary insulation of transistor gates from leakage currents, and optical lithography techniques were improved to allow patterning of 30 nanometer features.[64] These advances depended on basic advances in nanofabrication and characterization that took place during the prior decade, and "[c]ontinued scaling will require further fundamental advances," perhaps involving carbon nanotubes or graphene.[65]

B. Nanotechnology's Economic Contribution

This Section evaluates how nanotechnology has transformed economic activity and the nature of innovation from both qualitative and quantitative perspectives.

1. Qualitative Analysis of Nanotechnology's Transformative Potential

As explained above, nanotechnology has had an impact on a vast range of technological fields, and it has been compared to prior general purpose technologies. At a 2013 forum convened by the U.S. Government Accountability Office with participants selected by the National Academies, multiple participants thought nanomanufacturing has the potential to transform society as significantly as innovations such as electricity, computers, and the internet.[66] For example, nanomanufacturing "will increasingly allow mass reproducibility at an extremely precise scale" and "could open new world markets" by making "low cost goods similar in function to existing products."[67] There are potential applications across a huge range of sectors, from improved battery-powered vehicles to more targeted medical therapies to nanotube-enhanced road pavement with remote sensing capabilities.[68]

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[62] WORLD TECH. EVALUATION CTR., supra note 5, at 7 tbl.2.

[63] *Id.* at 377.

[64] *Id.* at 378.

[65] *Id.* at 378, 381-82, 399-403.

[66] U.S. GOV'T ACCOUNTABILITY OFFICE, NANOMANUFACTURING: EMERGENCE AND IMPLICATIONS FOR U.S. COMPETITIVENESS, THE ENVIRONMENT, AND HUMAN HEALTH 13 (2014), *available at* http://www.gao.gov/assets/670/660591.pdf.

[67] *Id.* at 13, 15.

[68] *Id.* at 14.

In addition to opening new markets and fostering economic growth, nanotechnology also has the potential to enhance social welfare by addressing global sustainability challenges. There has been significant progress in developing nanotechnology-based solutions for water treatment, desalination, and reuse, and nanotechnology has the potential to provide even more efficient and cost-effective solutions. [69] Nanotechnology researchers have also improved food safety and biosecurity, produced lightweight but strong nanocomposities for building more fuel-efficient vehicles, created methods for separating carbon dioxide from other gases, and dramatically improved the efficiency of plastic solar cells.[70] The ability to shape the world at the nanoscale has truly amazing possibilities.

2. Quantitative Estimates of the Nanotechnology Market

Quantifying the total economic impact of all developments in nanotechnology—not just the ones discussed above—is challenging. The Organization for Economic Cooperation and Development (OECD) and the U.S. National Nanotechnology Initiative (NNI) held a 2012 symposium focused on this question, although it raised more questions than answers.[71] One problem is that much of the information about nanotechnology's market value is proprietary and in the hands of private businesses. But even with perfect information, challenges in assessing nanotechnology's impact include (1) determining what outcomes to measure, (2) assessing the value of a nanotechnology invention that is a small but fundamental component of a product or process; and (3) deciding which products and services fall within the bounds of "nanotechnology."[72]

Metrics for assessing the impact of government investments in nanotechnology include direct outputs such as scientific publications and patents, short-term outcomes such as graduates with nanotechnology-focused degrees and technology transfer awards for small businesses, and longer-term outcomes such as nanotechnology companies, jobs, products, and sales.[73] Each of these can be useful; for example, patent citation analysis can help assess the downstream influences of an R&D program on diverse areas, or to trace backwards from some outcome of significance.[74] But of most interest is some measure of the social benefit of nanotechnology, and the most common proxy for social benefit is the economic market value, which is the focus of this Section. It is worth keeping in mind, however, that social benefit is not always captured by market value.[75] For example, since the Japanese nuclear accident of 2011, Japan has focused more attention on measuring the benefits of technology in terms of increased safety, security, sustainability, and quality of life.[76]

Even when limiting the query to market impact, it is often difficult to assess the value that nanotechnology adds to a given product or process. For example, the size of

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[69] WORLD TECH. EVALUATION CTR., *supra* note 5, at 226-28.

[70] *Id.* at 229-30, 237, 280.

[71] ORG. FOR ECON. CO-OPERATION & DEV., *supra* note 3.

[72] *Id.* at 8.

[73] *See* NAT'L RESEARCH COUNCIL, TRIENNIAL REVIEW OF THE NATIONAL NANOTECHNOLOGY INITIATIVE 66 (2013), *available at* http://www.nap.edu/openbook.php?record_id=18271.

[74] ORG. FOR ECON. CO-OPERATION & DEV., *supra* note 3, at 68.

[75] *See* Daniel J. Hemel & Lisa Larrimore Ouellette, *Beyond the Patents–Prizes Debate*, 92 TEX. L. REV. 303, 328-29 (2013).

[76] ORG. FOR ECON. CO-OPERATION & DEV., *supra* note 3, at 52.

features in modern semiconductors is typically in the nanoscale range, and the markets for semiconductors and electronics as a whole are over $200 million and $1 trillion, respectively.[77] But it is unclear how much of these values should be attributed to nanotechnology.

The United Kingdom Department for Environment, Food, and Rural Affairs has developed a valuation methodology based on comparing a nanotechnology-enabled product with an existing, non-nanotechnology product to try to extract value that nanotech adds.[78] Based on this method, the value added to the UK economy by some nano-enabled products was "quite modest,"[79] although the specific products and measured value were not reported. A different approach to measuring the impact of government R&D investments is taken by the U.S. STAR METRICS program, which attempts to link inputs to outputs and outcomes.[80] However, this project is still in its early stages and has not reached any nanotechnology-specific conclusions.

Assessing the overall market value of nanotechnology-enabled goods and services (without worrying about market substitution) is somewhat easier, but such calculations still face the definitional problem of how large to draw the nanotechnology umbrella. A few countries have adopted their own classification systems. For example, the Russian Federation has classified nanotechnology-enabled goods and services and, based on data collected in business surveys since 2010, estimates overall nano-related sales in Russia at $6 billion per year.[81] However, there are no uniform global standards for nanotechnology classification.

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[77] *Id.* at 61.

[78] Katherine Bojczcuk & Ben Walsh, *Models, Tools and Metrics Available To Assess the Economic Impact of Nanotechnology* (OECD/NNI Int'l Symposium on Assessing the Economic Impact of Nanotechnology Background Paper 4, 16 Mar. 2012), *available at* http://www.oecd.org/sti/nano/49932079.pdf.

[79] ORG. FOR ECON. CO-OPERATION & DEV., *supra* note 3, at 47.

[80] *See* Julia Lane & Stefano Bertuzzi, *Measuring the Results of Science Investments*, 331 SCIENCE 678, 679 (2011); U.S. Dep't of Health & Human Servs., *About Star Metrics*, STAR METRICS, https://www.starmetrics.nih.gov/Star/About (last visited Dec. 1, 2014).

[81] ORG. FOR ECON. CO-OPERATION & DEV., *supra* note 3, at 44-45.

The most frequently cited figures for the global nanotechnology market come from the consulting firm Lux Research, which estimates that "total sales of final products that incorporate emerging nanotech . . . grew from $339 billion in 2010 to $731 billion in 2012."[82] Given Lux Research's consulting role, this should be treated as an upper bound on the size of the nanotechnology market under an expansive definition.[83] Lux Research's definition of nanotechnology requires "purposeful engineering" and "size-dependent" effects, and thus excludes accidental nanomaterials and semiconductor chips with sub-100 nanometer features that do not involve any nanoscale effects.[84] Another firm, BCC Research, noted the "hype" caused by grouping diverse technologies under the heading of "nanotechnology," and used a narrower definition that resulted in a significantly smaller estimate of $22.9 billion in 2013.[85] But a different report from BCC Research estimated the nanomedicine market alone at $50.1 billion in 2011.[86]

Mihail Roco, the chair of the U.S. National Science and Technology Council's subcommittee on Nanoscale Science, Engineering and Technology, and the Senior Advisor for Nanotechnology at the National Science Foundation, has performed his own research into nanotechnology market value and has summarized the key indicators of nanotechnology development in 2000 and 2010 as follows:

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[82] Lux Research Inc., Nanotechnology Update: Corporations Up Their Spending as Revenues for Nano-enabled Products Increase 2 (2014).

[83] Lux Research has a disclaimer that while the report is "based on information obtained from sources believed to be reliable," "investors should be aware that the firm may have a conflict of interest that could affect the objectivity of this report." *Id.* at 1. The report was conducted with funding support from the U.S. National Nanotechnology Coordination Office and the U.S. National Science Foundation. *Id.* at 2; *see also* Press Release, Nat'l Sci. Found., Market Report on Emerging Nanotechnology Now Available (Feb. 25, 2014), *available at* http://www.nsf.gov/news/news_summ.jsp?cntn_id=130586 ("NSF and NNCO-funded independent study identifies more than $1 trillion in global revenue from nano-enabled products in 2013.").

[84] 1 Lux Research Inc., The Nanotech Report 1-3 (5th ed. 2007).

[85] BCC Research, Nanotechnology: A Realistic Market Assessment: Report Overview (2014), *available at* http://www.bccresearch.com/market-research/nanotechnology/nanotechnology-market-assessment-report-nan031f.html (free download of the report overview).

[86] BCC Research, Nanotechnology in Medical Applications: The Global Market: Report Overview (2012), *available at* http://www.bccresearch.com/market-research/healthcare/nanotechnology-medical-applications-global-market-hlc069b.html.

Table 1. Indicators of Nanotechnology Development[87]

	Primary Workforce	Papers in SCI-Indexed Journals	Patent Applications	Market Value of Final Products	Public & Private R&D Funding	Venture Capital
2000	60,000	18,000	1,200	$30B	$1.2B	$0.21B
2010	600,000	80,000	20,000	$300B	$18B	$1.3B

II. The Nanotechnology Innovation Ecosystem

This Part describes the nanotechnology innovation ecosystem. Section II.A describes the array of mechanisms through which governments provide support for nanotechnology innovation, with a focus on direct financial transfers through grants and similar programs. Section II.B then turns to the actors within this ecosystem—including national laboratories, universities, large corporations, and small start-ups—and Section II.C examines the mechanisms through which they interact.

A. State Support for Nanotechnology R&D

The state supports innovation in nanotechnology and other fields through a variety of policy levers. Most obviously, governments facilitate financial transfers to innovators to help close gaps between the cost of R&D projects and the private value that innovators could appropriate absent government intervention, which is often smaller than the social value of an invention.[88] These laws will be the focus of this Section. But many other fields of law have a substantial impact on innovation, including tort law, immigration and human capital law, antitrust law, and more.[89] Of particular relevance to nanotechnology are environmental and safety regulations, as many governments have debated how to address concerns about negative impacts from nanotechnology without stifling innovation in the field.[90]

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[87] Mihail C. Roco, *Nanotechnology: From Discovery to Innovation and Socioeconomic Projects*, CHEMICAL ENGINEERING PROGRESS, May 2011, at 21, 22 tbl.1. Roco's dollar estimates are based on direct contacts with industry and government leaders in nanotechnology; his workforce estimates are based on the "conservative" assumption that each worker would contribute $500,000 to revenue per year. E-mail from Mihail C. Roco, Senior Advisor for Nanotechnology, Nat'l Sci. Found., to Lisa Larrimore Ouellette, Assistant Professor of Law, Stanford University (Jan. 8, 2015, 07:57 PST) (on file with author).

[88] *See* Hemel & Ouellette, *supra* note 75, at 310-15.

[89] *See* THE KAUFFMAN TASK FORCE ON LAW, INNOVATION, AND GROWTH, RULES FOR GROWTH: PROMOTING INNOVATION AND GROWTH THROUGH LEGAL REFORM (2011), *available at* http://www.kauffman.org/~/media/kauffman_org/research%20reports%20and%20covers/2011/02/rulesforgrowth.pdf.

[90] For a detailed discussion of nanotechnology environmental, health, and safety issues, see WORLD TECH. EVALUATION CTR., supra note 5, at 159-206. When determining how to regulate nanotechnology, governments should be aware of the potential that the field could develop the polarizing political valence of environmental and technological risks such as global warming, nuclear power, and genetically modified foods. *See* Dan M. Kahan et al., *Cultural Cognition of the Risks and Benefits of Nanotechnology*, 4 NATURE NANOTECHNOLOGY 87 (2009).

Governments facilitate financial transfers to innovators through direct R&D spending through grants and procurement contracts (including spending on national laboratories), innovation prizes, R&D tax incentives, and various forms of intellectual property (including the patent-like reward of regulatory exclusivity).[91] In theory, all of these incentives can accomplish the same goal. IP transfers rewards to innovators through supracompetitive prices on protected products or services, and IP imposes as much of a cost on society as policies that transfer the same amount through more traditional taxing and spending, even though this transfer is not reflected in government budgets.[92]

In practice, however, there are important differences in the efficacy of these different transfer mechanisms. One distinction is whether governments tailor rewards on a project-by-project basis, or simply establish technology-neutral ground rules. Grants and fixed prizes are most effective when the government can foresee a potential invention and evaluate its costs and benefits. In contrast, patents and tax incentives leverage private information about potential projects.[93] Another distinction is whether the reward is transferred early in the R&D process, or only ex post to successful projects. Ex post rewards such as patents and prizes provide a strong incentive for success, but in some cases that incentive might be dulled because ex post rewards are both delayed and speculative, rendering ex ante rewards like grants and tax credits more efficient.[94]

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[91] *See* Hemel & Ouellette, *supra* note 75, at 315-326 (describing how these policies are implemented in the United States).

[92] *See id.* at 371 (discussing how patents act as a “shadow tax”).

[93] *See id.* at 327-33.

[94] *See id.* at 333-45. In contrast, optimism bias can make ex post rewards appear more cost effective, though it can also cause inventors to inefficiently invest in projects with negative net present value. And optimism bias cannot offset the combined effects of capital constraints and risk aversion because the private rate of return on R&D spending is greater than the rate of return on ordinary capital investment. *Id.* at 340-42.

This Section will primarily focus on direct funding of nanotechnology R&D through grants, national laboratories, and procurement contracts; Part III will turn to the role of intellectual property. But the other mechanisms for facilitating transfers to innovators should not be ignored. In particular, R&D tax incentives provide significant transfers to innovators, although calculating the nanotechnology-specific portion of this transfer is difficult. The two largest R&D tax incentives in the United States, sections 41 and 174 of the Internal Revenue Code, cost over $10 billion per year,[95] and worldwide, tens of billions of dollars are spent each year on R&D tax incentives.[96] In addition to these technology-neutral incentives, at least six U.S. states have enacted nanotechnology-specific tax incentives,[97] and a federal nanotechnology tax incentive has been proposed.[98] Innovation prizes are also a growing policy choice in the United States,[99] and while they are not yet a major tool in the nanotechnology space, a federal nanotechnology prize has been proposed,[100] and there are private non-profit prizes.[101]

Most nanotechnology-specific state support, however, has come in the form of direct grants, both for basic research and for early-stage commercialization projects. Over sixty countries created national nanotechnology R&D programs between 2001 and 2004.[102] The first and largest such program is the U.S. NNI, which has provided nearly $20 billion in support since 2000 through numerous federal agencies.[103] There are also over twenty nanotechnology initiatives run by U.S. state and local governments.[104]

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[95] *See* STAFF OF THE JOINT COMM. ON TAXATION, 113TH CONG., ESTIMATES OF FEDERAL TAX EXPENDITURES FOR FISCAL YEARS 2012-2017, at 30 tbl.1 (Comm. Print 2013).

[96] *See* ORG. FOR ECON. COOPERATION & DEV., THE INTERNATIONAL EXPERIENCE WITH R&D TAX INCENTIVES 4 fig.1 (2011), *available at* http://www.finance.senate.gov /imo/media/doc/OECD%20SFC%20Hearing%20testimony%209%2020%2011.pdf.

[97] *See* ILL. COMP. STAT. ANN. 5/220; MINN. STAT. ANN. § 116J.8737; NEB. REV. STAT. § 77-6302; VA. CODE ANN. § 58.1-339.4; WIS. STAT. ANN. § 238.15. Arkansas enacted a nanotechnology research tax credit in 2001 but repealed it in 2009. *See* 2001 Arkansas Laws Act 1284 (H.B. 2237) (codified at ARK. CODE ANN. § 15-4-2104); 2009 Arkansas Laws Act 716 (H.B. 2081) (repealing the 2001 legislation).

[98] H.R. 394, 113th Cong. (2013); H.R. 2749, 112th Cong. (2011); H.R. 820, 111th Cong. (2009); H.R. 3235, 110th Cong. (2007).

[99] *See* Hemel & Ouellette, *supra* note 75, at 317-19.

[100] *See* S. 596, 111th Cong. (2009); H.R. 6661, 110th Cong. (2008); S. 3269, 110th Cong. (2008).

[101] For example, the Foresight Institute has established a $250,000 prize for demonstration of a 50-nanometer 8-bit adder and a 100-nanometer robot arm. *See Feynman Grand Prize*, FORESIGHT INST., http://www.foresight.org/GrandPrize.1.html (last visited Jan. 15, 2015).

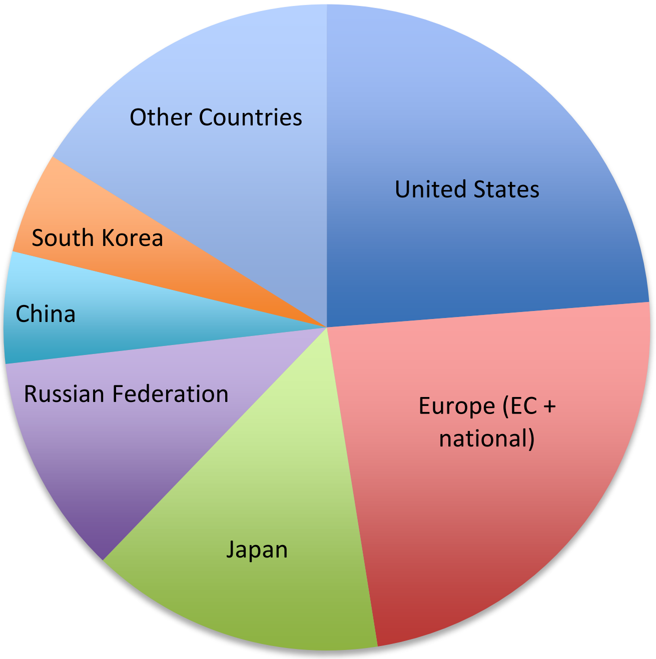
[102] WORLD TECH. EVALUATION CTR., supra note 5, ix.

[103] *See* SUBCOMMITTEE ON NANOSCALE SCIENCE, ENGINEERING, AND TECHNOLOGY, OFFICE OF SCIENCE AND TECHNOLOGY POLICY, *supra* note 2, at 7; WORLD TECH. EVALUATION CTR., supra note 5, at 4; *see also* 21st Century Nanotechnology Research and Development Act (2003), Pub. L. No. 108-153, § 6, 117 Stat. 1923, 1929 (codified at 15 U.S.C. § 7505 (2004)) (authorizing nanotechnology-related expenditures).

[104] *See* NAT'L NANOTECHNOLOGY INITIATIVE, REGIONAL, STATE, AND LOCAL INITIATIVES IN NANOTECHNOLOGY: REPORT OF THE NATIONAL NANOTECHNOLOGY INITIATIVE WORKSHOP, MAY 1-2, 2012, PORTLAND, OREGON (2013), *available at* http://www.nano.gov/sites/default/files/pub_resource/nni_rsl_2012_rpt_0.pdf; NAT'L RESEARCH

Global government spending on nanotechnology R&D was $7.9 billion in 2012, led by the United States and the European Union (including both national governments and the European Commission) with about $2.1 billion in spending each.[105] (Within Europe, the largest funders were Germany, France, Switzerland, the United Kingdom, and Sweden.[106]) Next were Japan at $1.3 billion, Russia at $974 million, and China and South Korea at just under $500 million each.[107] The next largest spenders were Canada, Taiwan, Brazil, Singapore, Israel, and India.[108] The breakdown of global government spending in 2012 is illustrated in Figure 1.

Figure 1. Direct Government Nanotechnology Spending (as share of $7.9B total in 2012)



Total estimated government expenditures for the earlier period of 2001 to 2009 are approximately $11 billion by the United States, $10 billion by the European Union (including both European Commission and national funding), $8 billion by Japan, and $13 billion by other countries.[109] The European Commission currently spends about €600 million ($676 million) per year on nanotechnology.[110]

Of course, whom this money is given to, and with what strings attached, is critical to its effectiveness. A review of the U.S. NNI by the President's Council of Advisors on Science and Technology recommended that more money be directed to "grand challenges" with specific, measurable goals such as "the reduction in the specific

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COUNCIL, *supra* note 73, at 93 (describing New York's support for the College of Nanoscale Science and Engineering at the University of Albany); *Regional, State, and Local (RSL) Nanotechnology Initiatives and Resources*, NAT'L NANOTECHNOLOGY INITIATIVE, http://www.nano.gov/initiatives/commercial/state-local (last visited Jan. 15, 2015).

[105] LUX RESEARCH INC., *supra* note 82, at 3.

[106] *Id.* at 4.

[107] *Id.*

[108] *Id.*

[109] WORLD TECH. EVALUATION CTR., supra note 5, at 17 tbl.5.

[110] ORG. FOR ECON. CO-OPERATION & DEV., *supra* note 3, at 22.

energy consumption of seawater desalination to below 1.5 kWh/m^3" or the development of solid-state refrigeration systems with energy performance that meets certain quantitative metrics.[111]

Also, as noted previously, the figures presented above include only direct transfers from the government, such as through grants, national laboratories, and small-business commercialization awards. The size of other government-facilitated transfers, including through the IP and R&D tax incentive systems, are more difficult to estimate but no less important when considering nanotechnology innovation policy. The following Section turns to the different actors who are supported by this complex web of innovation laws.

B. Nanotechnology R&D Actors

The nanotechnology innovation ecosystem comprises diverse actors, including government laboratories, universities and other nonprofit research institutions, large businesses, and small start-ups. There are also an array of venture capitalists and other intermediaries that have emerged to help facilitate capital and knowledge flows among these actors. Of course, the specific actors that emerge in an innovation ecosystem depend on the background of innovation laws. For example, greater government reliance on ex post transfer mechanisms like patents, rather than ex ante mechanisms like grants and tax credits, encourages the development of financing mechanisms to help firms bridge the gap between R&D expenditures and the resulting patent-based rewards.[112]

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[111] PRESIDENT'S COUNCIL OF ADVISORS ON SCI. & TECH., REPORT TO THE PRESIDENT AND CONGRESS ON THE FIFTH ASSESSMENT OF THE NATIONAL NANOTECHNOLOGY INITIATIVE 30-31 (2014), *available at* http://www.whitehouse.gov/sites/default/files/microsites/ostp/PCAST/pcast_fifth_nni_review_oct2014_final.pdf.

[112] *See* Hemel & Ouellette, *supra* note 75, at 357-58.

As described in the previous section, governments themselves are critical actors in the nanotechnology ecosystem. Not only do they provide the laws and financial support necessary for private-sector innovation to thrive, but they also perform a significant amount of R&D through national laboratories or state-supported universities. For example, much of the Chinese government's $1 billion in nanotechnology investment from 2001 to 2010 was spent on direct funding of research at state universities and at institutes and affiliates of the Chinese Academy of Sciences.[113] Brazil has created fifteen science and technology institutes working on nanotechnology, which employ about 2500 researchers.[114] The International Iberian Nanotechnology Laboratory in Portugal employs about 200 scientists.[115]

Private universities and other nonprofit research institutes are also major players in the nanotechnology innovation ecosystem, largely operating off of government grants. Because much university research is published, one way to estimate the leading nanotechnology research universities (both public and private) is to look at total publications. As illustrated in Table 2, while the United States leads in total publications (not all of which are from universities), its publications are split between many institutions. The institutions with the largest number of nanotechnology publications are the Chinese and Russian Academies of Sciences, the Centre National de la Recherche Scientifique (CNRS) in France, and three Japanese universities.

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[113] *See* Richard P. Applebaum et al., *Developmental State and Innovation: Nanotechnology and China*, 11 GLOBAL NETWORKS 298, 300-04 (2011); Sujit Bhattacharya et al., *China and India: The Two New Players in the Nanotechnology Race*, 93 SCIENTOMETRICS 59, 64 (2012).

[114] ORG. FOR ECON. CO-OPERATION & DEV., *supra* note 3, at 20.

[115] *Id.* at 59.

Table 2. Top Countries and Institutions by Number of Nanotechnology Publications Indexed in Web of Science 1991-2012[116]

Rank	Country	Publications	Institution	Publications
1	USA	204,273	Chinese Acad. Sci.	29,591
2	China	146,420	Russian Acad. Sci.	12,543
3	Japan	75,850	CNRS (France)	8,105
4	Germany	50,891	Univ. Tokyo	6,932
5	France	44,503	Osaka Univ.	6,613
6	South Korea	41,907	Tohoku Univ.	6,266
7	England	34,246	U.C. Berkeley	5,936
8	India	22,285	CSIC (Spain)	5,585
9	Italy	21,474	Univ. Illinois	5,580
10	Russia	21,182	MIT	5,567
11	Spain	21,054	Nat’l Univ. Singapore	5,535
12	Canada	20,960	Univ. Sci. & Tech. China	5,527
13	Taiwan	18,449	Peking Univ.	5,294
14	Australia	14,728	Indian Inst. Tech.	5,123
15	Switzerland	13,664	Univ. Cambridge	5,040
16	Netherlands	12,266	Nanjing Univ.	5,035
17	Singapore	10,147	Zhejiang Univ.	4,836
18	Poland	7,953	Seoul Nat’l Univ.	4,831
19	Brazil	7,097	CNR (Italy)	4,679
20	Sweden	6,624	Kyoto Univ.	4,540

Another metric for universities is their graduates. Within the United States, the universities that awarded the largest number of nanoscience Ph.D.s from 1999 to 2009 are MIT, Berkeley, Northwestern, Georgia Tech, the University of Texas at Austin, the University of Illinois at Urbana-Champaign, Michigan, Stanford, Minnesota, and Cornell.[117]

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[116] Hsinchun Chen et al., *supra* note 50, at 8 tbl.5, 9 tbl.6.

[117] James P. Walsh & Claron Ridge, *Knowledge Production and Nanotechnology: Characterizing American Dissertation Research, 1999-2009*, 24 TECH. IN SOC’Y 127, 131 tbl.2 (2012).

Corporations of all sizes are also important actors in the nanotechnology R&D ecosystem. Global corporate spending on nanotechnology R&D was $8 billion in 2010, $9.5 billion in 2011, and $10 billion in 2012,[118] though it is unclear how much of this was subsidized by governments through R&D tax incentives. For comparison, recall that global direct government spending on nanotechnology R&D was $7.9 billion in 2012.[119] That corporate spending now likely exceeds government spending is some indication of the commercial viability of nanotechnology. The countries with the largest corporate spenders were the United States, Japan, and Germany, whose companies spent a combined $7.0 billion in 2012.[120]

These corporate spenders are numerous and diverse. From 1990 to 2008, about 17,600 companies worldwide (including 5,440 in the United States) published about 52,100 articles and applied for about 45,050 patents related to nanotechnology.[121] IBM was the top holder of U.S. nanotechnology patents in both 2004 and 2010.[122] The share of nanotechnology research done by small firms has grown over time, at least in the United States: from 1996 to 2006, the share of small-firm patents among all applications owned by U.S. companies grew from about 28% to 45%.[123]

Some of the earliest nanotechnology companies began to operate around 1990; for example, Nanophase Technologies began in 1989, Helix Energy Solutions Group in 1990, Zyvex in 1997, and Nano-Tex in 1998.[124] In 2007, Lux Research created a detailed report with profiles of 121 representative companies active in nanotechnology, including startups like SDCmaterials, small corporations like Nanophase, and large corporations with significant nanotechnology activities like BASF and DuPont.[125] A number of companies shared their views during the OECD's 2012 symposium on assessing the economic value of nanotechnology, including large corporations such as Lockheed Martin and Michelin (each of whom reported nanomaterials research that has led to substantial cost savings) and smaller firms such as Zyvex Technologies (which describes itself as the "world's first molecular nanomaterial company"), CytImmune Sciences (a nanomedicine company), and QD Vision (an MIT spinoff that produces quantum dots).[126]

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[118] LUX RESEARCH INC., *supra* note 82, at 5.

[119] *See supra* note 105 and accompanying text.

[120] LUX RESEARCH INC., *supra* note 82, at 5.

[121] Philip Shapira et al., *National Innovation Systems and the Globalization of Nanotechnology Innovation*, 36 J. TECH. TRANSFER 587, 592 (2011).

[122] WORLD TECH. EVALUATION CTR., supra note 5, at 598 tbl.5.

[123] Andrea Fernández-Ribas, *International Patent Strategies of Small and Large Firms: An Empirical Study of Nanotechnology*, 27 REV. POL'Y RES. 457, 463 (2010).

[124] *See Nanotechnology Timeline*, *supra* note 8.

[125] 2 LUX RESEARCH INC., *supra* note 84. The report summarizes factors such as each company's market, revenue, VC funding, corporate relationships, and IP. *Id.*

[126] ORG. FOR ECON. CO-OPERATION & DEV., *supra* note 3, at 53-61.

C. Knowledge Flows and Mechanisms Linking Nanotechnology Actors

The prior Section provided an overview of the actors in the nanotechnology innovation ecosystem, including government laboratories, universities and other nonprofits, and a variety of corporations. But what mechanisms link these actors, and how does knowledge flow among them?

The clearest quantitative metrics for technology transfer are formal license agreements and citation-based measures, but these metrics miss the substantial amount of transfer that occurs through more informal channels. The U.S. National Academies report on the U.S. NNI concluded: “The most widespread mechanism for technology transfer is publications and presentations of technical findings at conferences, workshops, tutorials, webinars, and the like. The importance of these activities cannot be overstated.”[127] The report highlights the role of professional societies like the American Physical Society and the Institute of Electrical and Electronics Engineers in facilitating these interactions through their conferences.[128]

New technologies sometimes follow an orderly progression from academic research to corporate development to a marketed product, but nonlinear paths are also common.[129] Venture capital (VC) is the traditional bridge between academic and industry, but global VC investment in nanotechnology was only $580 million in 2012, which is just three percent of the overall funding of $7.9 billion from governments plus $10 billion from corporations.[130] Instead, governments and established, cash-rich firms play a more critical role in facilitating nanotechnology development.[131]

One way in which governments facilitate technology transfer is by supplying essential nanotechnology infrastructure than can be used by a variety of actors. Nanotechnology R&D tends to be very capital intensive, with research often requiring clean rooms that house expensive fabrication and measurement tools (such as the specialized microscopes described in Section I.A.1). The U.S. National Science Foundation funded fourteen facilities at U.S. universities that composed the National Nanotechnology Infrastructure Network.[132] Members of the network, such as the Cornell NanoScale Facility and the Stanford Nanofabrication Facility, provided support for nanoscale fabrication and characterization for all qualified users, including corporations.[133]

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[127] NAT’L RESEARCH COUNCIL, *supra* note 73, at 95.

[128] *Id.* at 36.

[129] PRESIDENT’S COUNCIL OF ADVISORS ON SCI. & TECH., *supra* note 111, at 42.

[130] LUX RESEARCH INC., *supra* note 82, at 3, 5-6.

[131] *See* Tom Crawley et al., *Finance and Investor Models in Nanotechnology* (OECD/NNI International Symposium on Assessing the Economic Impact of Nanotechnology, Background Paper 2), *available at* https://www.nano.gov/sites/default/files/dsti_stp_nano201215.pdf.

[132] *About Us*, NAT’L NANOTECHNOLOGY INFRASTRUCTURE NETWORK, http://www.nnin.org/about-us (last visited Dec. 1, 2014).

[133] *Id.*

Governments also use direct grants to help transfer technologies from academia to industry. In the United States, the Small Business Innovation Research (SBIR) program provides grants to small businesses for commercialization projects, and the Small Business Technology Transfer (STTR) program provide grants to support public/private partnerships.[134] These programs awarded $100 million in nanotechnology grants across agencies in 2012.[135] Direct government support has also helped launch nanotechnology firms outside the United States; for example, government funding accounts for half of the €90 million ($100 million) investment in the German firm Inno.CNT, for over forty percent of the €107 million ($120 million) investment in Genesis in France, and for $8 billion of investment in the Russian initiative RUSNANO.[136] China's Local Development and Reform Commission provides direct funding for commercialization projects, typically providing fifteen percent of the total funding needed to set up a company.[137] This direct funding helps mitigate the risk to firms entering nanotechnology markets, making their entry commercially feasible.

Large companies have also been active in helping commercialize nanotechnology products, including by funding academic research and by collaborating with smaller firms.[138] One study of global nanotechnology patents and firms concluded that in general, "[l]arge firms play a fundamental role in co-producing and transferring knowledge in nanotechnology by acting as a node of high centrality directly linking the industry's co-patenting network with public research."[139]

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[134] *Frequently Asked Questions—General Questions*, SBIR/STTR, http://www.sbir.gov/faq/general (last visited Jan. 15, 2015). These are not nanotechnology-specific programs, but The National Academies report noted that "nanotechnologies are not unusual in the challenges and obstacles faced in the movement of discoveries from the laboratory into application and use," so U.S. "agencies rely on existing technology-transfer tools and processes" rather than focusing significant resources on technology transfer. NAT'L RESEARCH COUNCIL, *supra* note 73, at 13. There are also many U.S. technology transfer programs at the state and regional level. *Id.* at 101.

[135] PRESIDENT'S COUNCIL OF ADVISORS ON SCI. & TECH., *supra* note 111, at 42.

[136] *See* ORG. FOR ECON. CO-OPERATION & DEV., *supra* note 3, at 30.

[137] *See* Applebaum, *supra* note 113, at 305. However, a 2009 assessment concluded that "the pathways from laboratory research to successful commercialization remain problematic" in China. Philip Shapira & Jue Wang, *From Lab to Market? Strategies and Issues in the Commercialization of Nanotechnology in China*, 8 ASIAN BUS. & MGMT. 461 (2009).

[138] ORG. FOR ECON. CO-OPERATION & DEV., *supra* note 3, at 54 (describing a collaboration between Airbus and Zyvex "to have nanocomposites on commercial planes within three years"); *id.* at 60 (noting that the Semiconductor Research Corporation "has funded substantial research in academia").

[139] Corine Genet et al., *Which Model of Technology Transfer for Nanotechnology? A Comparison with Biotech and Microelectronics*, 32 TECHNOVATION 205 (2012).

A different set of channels is used for knowledge flows between countries, including for the diffusion of nanotechnology to low- and middle-income countries. The traditional North/South dichotomy is less helpful for evaluating nanotechnology across countries; for example, the R&D environment in countries like China, India, Brazil, South Africa, and Mexico is in many ways closer to that in the United States, Europe, and Japan than to countries such as the Dominican Republic, Laos, and Rwanda.[140] Many lower-income countries see embrace of nanotechnology as a necessity to long-term economic growth, and some scholars have argued that intellectual property rights and trade barriers are limiting the development of nanotechnology R&D capacity in low-income countries.[141] Nanotechnology applications of particular interest to developing countries include energy storage, agricultural productivity enhancements, water treatment, and health technologies.[142]

As previously noted, over 60 countries are engaged with nanotechnology R&D on a national level, and a diverse set of countries have hosted and participated in nanotechnology conferences.[143] Some diffusion occurs through formal collaboration agreements, such as the International Center for Nanotechnology and Advanced Materials consortium involving U.S. and Mexican universities.[144] Nanotechnology also diffuses through skilled migration. Nanoscientists within the United States are overwhelmingly foreign born, and countries such as China and India have pursued "reserve brain drain" policies to spur the return migration of their nationals.[145] The role of foreign direct investment (FDI) in facilitating nanotechnology diffusion is less clear. For example, while China has been a popular destination for FDI in general, provinces with greater FDI do not appear to generate more nanotechnology patents; rather, nanotechnology development in China seems to be driven by public-sector investments.[146]

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[140] DONALD MACLURCAN, NANOTECHNOLOGY AND GLOBAL EQUALITY 135-36 (2012).

[141] *Id.* at 137, 147.

[142] *Id.* at 154.

[143] *Id.* at 197-201.

[144] *See* Guillermo Foladori & Edgar Zayago Lau, *Tracking Nanotechnology in México*, 4 NANOTECHNOLOGY L. & BUS. 213, 219 (2007); *see also* Luciano Kay & Philip Shapira, *Developing Nanotechnology in Latin America*, 11 J. NANOPARTICLE RES. 259 (2009) (documenting how different Latin American countries pursue strategies of within-country, regional, and international collaborations).

[145] James P. Walsh, *The Impact of Foreign-Born Scientists and Engineers on American Nanoscience Research*, SCI. & PUB. POL'Y (advance publication online 2014).

[146] Can Huang & Yilin Wu, *State-led Technological Development: A Case of China's Nanotechnology Development*, 40 WORLD DEV. 970, 975-78 (2012).

III. Role of IP Systems in Nanotechnology Developments

As described in Part II, the nanotechnology innovation ecosystem is deeply entwined with various public support structures. But one form of state support for innovation that has received little attention so far is intellectual property. Assessing the net impact of IP, or its efficacy relative to other innovation incentives, has proven difficult in general,[147] and there are no attempts to quantify its net social impact in nanotechnology. The dense nanotechnology patent landscape makes clear, however, that many firms at least see private benefits in nanotechnology patenting.

This Part examines the role that IP has played in nanotechnology's development, as well as the potential challenges ahead. Nanotechnology implicates all areas of IP. Trademarks are important for protecting an innovator's first-mover advantage, and the growth in nanotechnology has raised questions about whether the use of "nano" as a prefix should be regulated under trademark deceptiveness doctrines in the United States.[148] There also have been some creative examples of nanoscale art that raise questions of copyright law.[149]

This Part will focus, however, on the two primary IP mechanisms that firms use to appropriate returns on their nanotechnology R&D investments: patents and trade secrets. While there are no nanotechnology-specific surveys of what mechanisms firms use to appropriate returns on R&D, surveys of firms more broadly indicate that both patents and secrecy are used for appropriation, although their importance varies significantly by sector.[150]

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[147] *See* Lisa Larrimore Ouellette, *Patent Experimentalism*, 101 VA. L. REV. (forthcoming 2015) (reviewing this literature).

[148] Jason John Du Mont, *Trademarking Nanotechnology: Nano-Lies & Federal Trademark Registration*, 36 AIPLA Q.J. 147 (2008). As an example of the problems that misleading nano-branding can cause, the hospitalization of consumers who used the bathroom cleaner MAGIC NANO led to public outcry and the formation of a nanotechnology task force by the U.S. Food and Drug Administration even though the product did not actually contain nanomaterials. *Id.* at 148.

[149] *See, e.g.*, Steve Schlackman, *Artist Is in Trouble for Nanoscale Copies of an M.C. Escher*, ART L.J. (Nov. 22, 2014), http://artlawjournal.com/nanoscale-copy-mc-escher-copyright-infringement.

[150] *See* Wesley M. Cohen, Richard R. Nelson & John P. Walsh, *Protecting Their Intellectual Assets: Appropriability Conditions and Why U.S. Manufacturing Firms Patent (or Not)* (Nat'l Bureau of Econ. Research, No. 7552, 2000) (surveying 1478 R&D labs in the U.S. manufacturing sector in 1994 and finding that firms use patents and trade secrets as well as non-IP-based market incentives to appropriate returns on R&D, with the mix of tools varying by industry); Richard C. Levin et al., *Appropriating the Returns from Industrial Research and Development*, 1987 BROOKINGS PAPERS ON ECON. ACTIVITY 783, 798, 824 (surveying 650 industrial research managers and finding that only in the pharmaceutical industry were patents rated more effective than any other means of appropriation).

A. Patents

As Mark Lemley has explained, nanotechnology differs from many other important fields of invention over the past century in that many of the foundational inventions have been patented at the outset and in that many of the patents have been issued to universities.[151] By 2012, over 30,000 nanotechnology patents had been granted by the US Patent & Trademark Office (USPTO) alone.[152] Patentees generally find these patents valuable enough to maintain: a 2007 study found that owners had maintained 54% of pre-1994 patents through three maintenance periods, compared with 43% of patents generally.[153] While there have been some concerns about potential limitations on the patentability of nanotechnology, many more commentators have expressed the opposite concern that there are *too many* nanotechnology patents that will lead to inefficient patent thickets.

1. Potential Limitations on the Patentability of Nanotechnology

Although TRIPS generally requires patents on "any inventions . . . in all fields of technology," it allows exceptions that implicate some nanotechnology inventions, including for medical diagnostic methods and for inventions that could endanger health or the environment.[154] Additionally, some countries have limited what counts as a patentable "invention" in ways that may exclude certain nanotechnology developments from patentability. In particular, the U.S. Supreme Court has recently held that the judicially created "implicit exception" to patentable subject matter includes any "product of nature" such as genomic DNA (even in an isolated and purified form),[155] as well as any "law of nature" such as a method for calibrating the proper dosage of a drug.[156]

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[151] Mark A. Lemley, *Patenting Nanotechnology*, 58 STAN. L. REV. 601 (2005).

[152] Chen et al., *supra* note 50, at 5 tbl.2.

[153] 1 LUX RESEARCH INC., *supra* note 84, at 201.

[154] Agreement on Trade-Related Aspects of Intellectual Property Rights art. 27, Apr. 15, 1994, Marrakesh Agreement Establishing the World Trade Organization, Annex 1C, 1869 U.N.T.S. 299 [hereinafter TRIPS].

[155] Ass'n for Molecular Pathology v. Myriad Genetics, Inc., 133 S. Ct. 2107, 2111, 2116 (2013).

[156] Mayo Collaborative Servs. v. Prometheus Labs., Inc., 132 S. Ct. 1289, 1293-94 (2012); *see also* Alice Corp. Pty. v. CLS Bank Int'l, 134 S. Ct. 2347, 2355 (2014) (affirming that *Mayo* provides the framework for assessing exceptions to patentable subject matter).

These expansive patentable subject matter exceptions raise questions about the validity of many nanotechnology patents in the United States.[157] Many nanomaterials exist in nature; for example, carbon-based nanoparticles are produced by common candle flames,[158] and graphene is produced simply by writing with a pencil.[159] There do not appear to have been any challenges yet to nanotechnology patents under the Supreme Court's expanded patentable subject matter exceptions, perhaps due to the relative scarcity of nanotechnology patent litigation overall, but this could become a concern for patentees who end up wanting to assert their patents.

Nanotechnology inventions might also be found unpatentable for lack of novelty if the invention was "inherent" in the prior art (as for the inadvertent uses of nanoscale particles mentioned in Section I.A), or if they are merely nanoscale formulations of previously disclosed compounds.[160] But these do not seem to have been significant issues in practice. For example, the Technical Board of Appeals (TBA) of the European Patent Office (EPO) held in *BASF v. Orica Australia* that a prior patent that disclosed polymer nanoparticles larger than 111 nanometers did not destroy the novelty of nanoparticles smaller than 100 nanometers.[161] And the TBA held in *SmithKline Beecham v. Wyeth Holdings* that an application on a vaccine agent with 80–500 nanometer particles did not destroy the novelty of an agent with 60–120 nanometer particles.[162]

Even if an invention is novel, it could still be unpatentable for lack of inventive step (known as obviousness in the United States).[163] In the United States, "the mere change of the relative size of the [elements of an invention] will not endow an otherwise unpatentable combination with patentability."[164] As discussed in Part I, nanotechnology does not involve a "mere change" in size—most nanotechnology definitions require that the size confers novel properties.

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[157] Laura W. Smalley, *Will Nanotechnology Products Be Impacted by the Federal Courts' "Product of Nature" Exception to Subject-Matter Eligibility Under 35 U.S.C. 101?*, 13 J. MARSHALL REV. INTELL. PROP. L. 397 (2014).

[158] *See* Massimo Bottini & Tomas Mustelin, *Carbon Materials: Nanosynthesis by Candlelight*, 2 NATURE NANOTECHNOLOGY 599 (2007).

[159] P. Blake et al., *Making Graphene Visible*, 91 APPLIED PHYSICS LETTERS 063124 (2007).

[160] *See* PRABUDDHA GANGULI & SIDDHARTH JABADE, NANOTECHNOLOGY INTELLECTUAL PROPERTY RIGHTS: RESEARCH, DESIGN, AND COMMERCIALIZATION 28 (2012).

[161] *Id.*

[162] *Id.* at 28-29.

[163] TRIPS requires patents for inventions that "involve an inventive step." TRIPS, *supra* note 154, art. 27. This requirement is codified in the U.S. Patent Act at 35 U.S.C. § 103 (2012).

[164] *In re* Troiel, 274 F.2d 944, 949 (C.C.P.A. 1960).

One U.S. patent lawyer wrote that “patents have been refused [as obvious] even in situations where the change in form, proportion, or size brought about better results than the previous invention,” and he advised nanotechnology patent applicants to focus on elements of their invention other than a mere reduction in size.[165] But there is no evidence that this has been a significant barrier to patentability.[166]

2. Knowledge Diffusion Through Patent Disclosure

Under TRIPS, patentees must “disclose the invention in a manner sufficiently clear and complete for the invention to be carried out by a person skilled in the art.”[167] The disclosure of technical knowledge in patents has contributed to knowledge diffusion, as illustrated by patent-based knowledge diffusion networks.[168]

Although some scholars have doubted that scientists in fact read patents, a survey of nanotechnology researchers found that a substantial number of them do find useful technical information in patents, although the disclosure function of patents could be greatly improved.[169] Out of 211 researchers (primarily in the United States), 64% reported that they have read patents, and 60% of those reading patents for scientific reasons (rather than legal reasons) said they found useful technical information in patents.[170] Respondents reported that patents can show “how a particular device works”; they can “put the ideas and research in context and offer[] some plausible views as to” the respondents’ own research; and they can keep “you from going down a road that has already been traveled.”[171] Others stated that “protocols . . . are described that are not found in other published literature,” and that “the way a new technology is described is much more reliable and reproducible in a patent than in a scientific paper.”[172]

While this survey shows that patent disclosures are not useless, it also shows that the disclosure function of patents could be improved. The glass-half-empty view of the numbers above is that 36% of respondents have never read patents, and 40% of those reading for technical information did not find anything useful. The qualitative comments from those who did not find useful information in patents raised four general complaints:

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[165] Ronald A. Bleeker, *Patenting Nanotechnology*, MATERIALS TODAY, Feb. 2004, at 44.

[166] One of the few published judicial opinions finding a nanotechnology patent application to be invalid as obvious did not rely on this reasoning. *See In re* Mouttet, 686 F.3d 1322 (Fed. Cir. 2012).

[167] TRIPS, *supra* note 154, art. 29.

[168] Shan Jiang et al., *The Roles of Sharing, Transfer, and Public Funding in Nanotechnology Knowledge-Diffusion Networks*, 66 J. ASS’N FOR INFO. SCI. & TECH. (forthcoming 2015).

[169] Lisa Larrimore Ouellette, *Do Patents Disclose Useful Information?*, 25 HARV. J.L. & TECH. 545 (2012).

[170] *Id.* at 559-60.

[171] *Id.* at 561.

[172] *Id.*

> [P]atents are (1) confusingly written ("the language of patents is obscure"); (2) unreliable (patents do not "go through the same level of critical review that scientific articles face"); (3) duplicative of journal articles ("[t]here was no information in the patent that had not already appeared in the scientific literature"); and (4) out of date ("[t]he long time delay between filing an invention disclosure and the public issuance of a patent seems to make it very unlikely that patents will regularly be a useful source of research information in a field as rapidly moving as nanotechnology").[173]

Additionally, 62% of patent readers—which includes many of those readers who found useful technical information—thought the patents they read did not provide sufficient disclosure for a nanotechnology researcher to recreate the invention without additional information.[174] This finding raises questions about how well the enablement requirement is being enforced, at least for the U.S. patents that were the likely targets of this critique.

The disclosure function of nanotechnology patents might be improved by better enforcement of current disclosure requirements (such as through examiner training and peer review), a reduced time to patent publication (especially for patentees such as universities that have little need for secrecy), improved access to the patent literature through search and annotation tools, and incentives to cite patents in scientific publications.[175]

It is also worth recognizing that the disclosure requirements are a policy lever for limiting negative effects of overbroad patents. For example, more stringent enforcement of the U.S. written description requirement has been proposed as a way to prevent patent thickets.[176] But as discussed in the following Section, it is not evident that there is in fact a patent thicket problem in nanotechnology.

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[173] *Id.* at 561-62.

[174] *Id.* at 562.

[175] *Id.* at 571-87.

[176] J. Peter Paredes, *Written Description Requirement in Nanotechnology: Clearing a Patent Thicket?*, 88 J. PAT. & TRADEMARK OFF. SOC'Y 489 (2006).

3. Patent Thickets and Patent Litigation

Commentators have raising concerns about potential nanotechnology patent thickets since at least 2004.[177] The concern is that fragmented and overlapping patent rights will impede technological progress through bargaining breakdowns such as holdup effects that prevent anyone from developing a particular technology. One cause of overlapping rights has been patent offices' difficulty dealing with this new interdisciplinary technology that does not fit neatly into existing patent classification systems.[178] But despite these concerns, there is little evidence of actual patent thicket problems so far. This may be because the nanotechnology products market remains too young for these problems to surface, or it may be a sign that nanotechnology licensing markets have been more efficient than predicted.

There have been a number of nanotechnology patent cases in the United States, although nothing stands out about nanotechnology patent litigation as compared to patent litigation more generally. Courts have been asked to construe patent claim terms such as "nanocomposite"[179] and "nanoparticles."[180] In one high-profile case, Elan Pharmaceuticals won a $55 million jury verdict for reasonable royalties based on its claim that the first nanoparticle-based cancer therapy drug, Abraxane, infringed two of its nanoparticle formulation patents.[181] There does not appear to be systematic data on the number, cost, or outcomes of nanotechnology patent cases, and obtaining meaningful litigation outcome data is difficult because most cases settle on confidential terms. For example, Nanometrics, which supplies equipment for measuring nanoscale semiconductor devices, has been party to six U.S. patent cases as both a plaintiff and a defendant, but all of these cases appear to have settled.[182]

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[177] *See* Ted Sabety, *Nanotech Innovation and the Patent Thicket: Which IP Policies Promote Growth?*, 1 NANOTECHNOLOGY L. & BUS. 262 (2004). For later articles, see Raj Bawa, *Nanotechnology Patent Proliferation and the Crisis at the U.S. Patent Office*, 17 ALB. L.J. SCI. & TECH. 699 (2007); Raj Bawa, *Will the Nanomedicine "Patent Land Grab" Thwart Commercialization?*, 1 NANOMEDICINE 346 (2005); Douglas J. Sylvester & Diana M. Bowman, *Navigating the Patent Landscapes for Nanotechnology: English Gardens or Tangled Grounds?*, *in* BIOMEDICAL NANOTECHNOLOGY: METHODS AND PROTOCOLS (Sarah J. Hurst ed., 2011).

[178] *See* Raj Bawa, *Nanotechnology Patenting in the US*, 1 NANOTECHNOLOGY L. & BUS. 31 (2004); Vivek Koppikar et al., *Current Trends in Nanotech Patents: A View from Inside the Patent Office*, 1 NANOTECHNOLOGY L. & BUS. 24 (2004).

[179] Schultz v. iGPS Co. LLC, No. 10 C 0071, 2013 WL 212927, at *5 (N.D. Ill. Jan. 17, 2013).

[180] Cephalon, Inc. v. Celgene Corp., 985 F. Supp. 2d 171, 175 (D. Mass. 2013).

[181] *See* William F. Prendergast & Heather N. Schafer, *Nanocrystalline Pharmaceutical Patent Litigation: The First Case*, 5 NANOTECHNOLOGY L. & BUS. 157 (2008). The parties then settled for a one-time fee of $78 million. *See* Carolina Bolado, *Celgene Strikes $78M Deal in Elan Abraxane IP Suit*, LAW360 (Feb. 24, 2011), http://www.law360.com/articles/228152/celgene-strikes-78m-deal-in-elan-abraxane-ip-suit.

[182] The Lex Machina patent litigation database was searched on January 30, 2015, for cases in which Nanometrics Inc. was a party. *See* LEX MACHINA, https://lexmachina.com (last visited Jan. 30, 2015). The resulting six cases were all coded as likely settlements. For earlier orders in two of them, see Nanometrics, Inc. v. Nova Measuring Instruments, Ltd., No. C 06-2252SBA, 2007 WL 627920 (N.D. Cal. Feb. 26, 2007); KLA-Tencor Corp. v. Nanometrics, Inc., No. C 05-03116 JSW, 2006 WL 708661 (N.D. Cal. Mar. 16, 2006). An over-inclusive Lex Machina search for patent cases with keywords [nano* NOT nanosecond]

Some nanotechnology patent disputes illustrate the wide array of conflicts that businesses can face when investing in uncertain technologies. The quantum dots firm Evident Technologies had to file for bankruptcy as a result of unfavorable patent and trademark disputes, although it then reached an agreement with the patent plaintiff and emerged from bankruptcy.[183] In another case involving a licensing dispute, the court enjoined a German inventor from terminating a license agreement with Nano-Proprietary, a nanotechnology IP company.[184] Nano-Proprietary bought an exclusive right to sublicense the inventor's patents on using carbon nanotubes as cathodes in displays, which the parties had believed to have tremendous market potential, although Nano-Proprietary was unable to find any sub-licensees.[185]

A number of other patent disputes are profiled by Prabuddha Ganguli and Siddharth Jabade.[186] But these cases do not illustrate any thicket-related licensing difficulties. Nanotechnology patents may have problems such as slow time to issuance, imperfect screening at the patent office (particularly for disclosure requirements), large numbers of difficult-to-search patents,[187] and costly litigation, but these are problems that impact the patent system as a whole, not problems with the nanotechnology patent system.

B. Trade Secrets

The final piece of the nanotechnology IP system is trade secrecy law. As noted above, much nanotechnology research takes place at universities, which have no incentive to keep their inventions secret. But for many corporations, trade secrets are an attractive appropriation strategy. Trade secrets are most attractive where the cost of maintaining the secret is low compared with the cost of patenting, where the likelihood of reverse engineering or independent discovery of the invention is low, and where the technology is not likely to generate significant licensing revenues.[188] Because the difficulty of reverse engineering nanotechnology inventions may often weigh in favor of secrecy over patenting, the number of nanotechnology patents my understate corporate innovation in the field.[189]

Lux Research's 2007 report noted, unsurprisingly, that nanotechnology process innovations are particularly likely to be protected by trade secrets.[190] Among nanomaterials producers, those focused on ceramic nanomaterials, nanostructured

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resulted in 944 cases, with 102 resulting in a win on the merits for the patentee, 84 leading to a win for the accused infringer (based on invalidity or noninfringement), 519 ending in a likely settlement, and the remainder either resolved procedurally or still pending. While these numbers should not be used as a measure of nanotechnology patent litigation, they provide a rough sense of the number of filed cases resulting in settlement.

[183] *See* GANGULI & JABADE, *supra* note 160, at 135.

[184] Nano-Proprietary, Inc. v. Keesmann, No. 06 C 2689, 2007 WL 433100 (N.D. Ill. Jan. 30, 2007).

[185] *Id.*

[186] GANGULI & JABADE, *supra* note 160, at 136-175.

[187] For an pedagogical overview of how to look for nanotechnology prior art, see GANGULI & JABADE, *supra* note 160, at 67-88.

[188] *See* PATRICK M. BOUCHER, NANOTECHNOLOGY: LEGAL ASPECTS 73-74 (2008).

[189] Lemley, *supra* note 151, at 617.

[190] 1 LUX RESEARCH INC., *supra* note 84, at 238, 268.

metals, and catalysts were more likely to rely on trade secrets.[191] Specific companies protecting their IP with trade secrets include Aspen Aerogels, a startup with a nanoporous silica aerogel product, and Cap-XX, a small/midsized firm focusing on nanoporous carbon supercapacitor electrodes for mobile devices.[192]

There have already been significant trade secret disputes in the United States over nanotechnology. In 2000, Nanogen sued its former employee Donald Montgomery for trade secret misappropriation, arguing that the patent applications Montgomery had filed on nanotechnology biochips disclosed trade secrets owned by Nanogen.[193] The value of Montgomery's settlement payment to Nanogen is estimated to be about $11 million.[194] In another case, Agilent Technologies received a $4.5 million damages award after suing former employees for misappropriation of trade secrets related to liquid chromatography using nanoscale particles.[195]

Allegations of trade secret theft are not always so successful. NanoMech sued former employee Arunya Suresh for violating a non-disclosure agreement.[196] Suresh allegedly photocopied and emailed proprietary documents related to patent-pending nano-lubrication products before leaving NanoMech, and NanoMech argued that Suresh would inevitably disclose this information to her new employer, BASF.[197] The court concluded that the inevitable-disclosure doctrine applied only to cases in which plaintiffs threatened misappropriation of trade secrets, and not breach-of-contract claims, and so the court granted Suresh's motion for judgment on the pleadings.[198]

As in the patent litigation context, it is not clear that nanotechnology raises any special challenges in the trade secret context. Keeping knowledge secret rather than disclosing it in patent documents can impede its dissemination, and it is unclear whether strong legal protections for trade secrets are worth the costs.[199] But this is not a nanotechnology-specific concern. As this paper has explained, the nanotechnology innovation ecosystem is a microcosm of the full innovation ecosystem. And the role of the IP system in nanotechnology appears similar to its role in general, with all its costs and benefits.

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[191] *Id.* at 65, 96, 127.

[192] 2 LUX RESEARCH INC., *supra* note 84, at 29, 47.

[193] BOUCHER, *supra* note 188, at 75-76.

[194] *Id.* at 76.

[195] Agilent Technologies, Inc. v. Kirkland, No. CIV.A. 3512-VCS, 2010 WL 610725, at *31 (Del. Ch. Feb. 18, 2010).

[196] NanoMech, Inc. v. Suresh, No. 5:13-CV-05094, 2013 WL 4805692 (W.D. Ark. Sept. 9, 2013).

[197] *Id.* at *4-5.

[198] *Id.* at *7.

[199] *See* Robert G. Bone, *The (Still) Shaky Foundations of Trade Secret Law*, 92 TEX. L. REV. 1803 (2014).