

NANOTECHNOLOGY AND INNOVATION POLICY

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I. INTRODUCTION

Nanotechnology is the engineering of matter at scales less than about one hundred nanometers (one ten-millionth of a meter). From nanomedicines to nanoscale electronics to nanomaterials, nanotechnology has already had a substantial impact across a variety of industries and is predicted to be an important driver of future economic growth. As an enabling technology across a wide range of fields, nanotechnology presents a microcosm of the global innovation ecosystem. As described in this Article, the story of nanotechnology involves both substantial state funding and heavy use of the patent system. Governments around the world have played an essential role not only by funding basic research, but also by crafting infrastructure to lower the barriers to entry, and by providing substantial direct funding to firms to help mitigate the risk of entering uncertain nanotechnology markets.¹ Nanotechnology is thus a useful counterpoint both to the growing number of case studies on how innovation can flourish without intellectual property (“IP”), and to the myth of an independent private sector that produces breakthrough innovations without government intervention.

Traditionally, patent law has been seen as the primary policy tool to promote innovation.² But a growing wave of scholars have recognized that patent law is only one of many legal institutions that govern knowledge production, and have shifted their attention to the broader economic context in which patents operate.³ Given the difficulty of drawing robust empirical conclusions from economy-wide statistics, many researchers have turned to the case study methodology to explore how patents have actually been used in specific innovative fields.⁴

These studies have demonstrated that intellectual property is not always necessary for innovation; rather, significant creative activity regularly occurs without reliance on IP in fields including fashion,

1. See *infra* Part IV.A.

2. See, e.g., Dan L. Burk & Mark A. Lemley, *Policy Levers in Patent Law*, 89 VA. L. REV. 1575, 1576 (2003) (“Patent law is our primary policy tool to promote innovation, encourage the development of new technologies, and increase the fund of human knowledge.”).

3. See generally Robert P. Merges, *Economics of Intellectual Property Law*, in OXFORD HANDBOOK OF LAW AND ECONOMICS (Francesco Parisi ed., forthcoming 2015), <http://ssrn.com/abstract=2412251> [<http://perma.cc/NUZ5-AZEC>] (describing “second wave” IP scholarship, which shows “increased attention to IP rights in a broader economic context” by studying “fields where formal IP is absent” but there is nonetheless “significant creative activity”).

4. See Lisa Larrimore Ouellette, *Patent Experimentalism*, 101 VA. L. REV. 65, 78–79 (2015) (describing the merits and drawbacks of the case study approach and highlighting its frequent use in patent law debates).

cuisine, stand-up comedy, magic, roller derby names, and tattooing.⁵ The authors of these studies of “IP’s negative space” have claimed that the studies “cast[] (further) doubt on the coherence of the prevailing neoclassical economic assumptions underlying IP law.”⁶ These case studies, however, focus on relatively low-cost forms of cultural production that can be supported by informal norms and market incentives. There are still many capital-intensive fields in which research and development (“R&D”) projects will not be pursued absent some state-mediated financial transfer to innovators, whether through the IP system or otherwise, and there is a need for case studies in these fields.

Legal scholars are beginning to recognize the importance of case studies of innovation in these more capital-intensive fields. For example, Professors John Golden and Hannah Wiseman recently published a case study of the fracking industry that suggested that “patents play[ed] only a modest role”⁷ in the industry’s recent technological developments. Professor Amy Kapczynski has also undertaken a case study of the transnational public scientific network that develops flu vaccines, which operates “without recourse to conventional IP.”⁸ In contrast, as described in this Article, nanotechnology is a field in which innovation has flourished alongside heavy use of the patent system, including for fundamental inventions. Indeed, in an early look at nanotechnology patenting, Professor Mark Lemley argued that it is “nearly the first new field in almost a century in which the basic ideas are being patented at the outset.”⁹ Of course, it does not necessarily follow that patents have been essential in the development of nanotechnology — we cannot observe the counterfactual world in which patents do not exist (or do not exist in their current form). But this

5. See Christopher J. Buccafusco, *On the Legal Consequences of Sauces: Should Thomas Keller’s Recipes Be Per Se Copyrightable?*, 24 CARDOZO ARTS & ENT. L.J. 1121, 1122 (2007); David Fagundes, *Talk Derby to Me: Intellectual Property Norms Governing Roller Derby Pseudonyms*, 90 TEX. L. REV. 1093, 1096–97 (2012); Jacob Loshin, *Secrets Revealed: Protecting Magicians’ Intellectual Property Without Law*, in LAW AND MAGIC 123 (Christine A. Corcos ed., 2010); Dotan Oliar & Christopher Sprigman, *There’s No Free Laugh (Anymore): The Emergence of Intellectual Property Norms and the Transformation of Stand-Up Comedy*, 94 VA. L. REV. 1787, 1790 (2008); Aaron Perzanowski, *Tattoos & IP Norms*, 98 MINN. L. REV. 511, 512–13 (2013); Kal Raustiala & Christopher Sprigman, *The Piracy Paradox: Innovation and Intellectual Property in Fashion Design*, 92 VA. L. REV. 1687, 1689 (2006); see also Rochelle Cooper Dreyfuss, *Does IP Need IP? Accommodating Intellectual Production Outside the Intellectual Property Paradigm*, 31 CARDOZO L. REV. 1437, 1437 (2010) (studying intellectual production without intellectual property, or IP without IP).

6. Fagundes, *supra* note 5, at 1093.

7. John M. Golden & Hannah J. Wiseman, *The Fracking Revolution: Shale Gas as a Case Study in Innovation Policy*, 64 EMORY L.J. 955, 955 (2015).

8. Amy Kapczynski, *Order Without Intellectual Property Law: The Flu Network as a Case Study in Open Science I* (Mar. 12, 2015) (unpublished manuscript) (on file with author).

9. Mark A. Lemley, *Patenting Nanotechnology*, 58 STAN. L. REV. 601, 606 (2005).

difficulty is inherent in all case studies. The existence of nanotechnology and other fields that appear to be thriving alongside intensive use of IP at least serves as a note of caution about extrapolating from case studies of IP's negative space.

The substantial use of the patent system does not, however, mean that the state has played a backseat role in nanotechnology's history.¹⁰ Over sixty countries created national nanotechnology R&D programs between 2000 and 2004, and global government spending on nanotechnology R&D was about \$7.9 billion in 2012.¹¹ Only in the last five years has global corporate spending on nanotechnology R&D surpassed government spending — an indication of both the increasing commercial viability of nanotechnology and of the importance of government funding in reaching this stage. In contrast to the conventional narrative in the IP literature, which “typically describe[s] the state . . . as inertial, heavy, bureaucratic, ill-informed, and perilously corruptible and corrupt,”¹² this Article demonstrates that many governments have been active and innovative participants in the nanotechnology innovation ecosystem.¹³ The state has played an essential role not only by funding basic research, but also by creating infrastructure to lower the barriers to entry, and by providing substantial direct funding to firms to help mitigate the risk of entering uncertain nanotechnology markets.¹⁴

To provide context for the analysis of nanotechnology innovation, Part II describes the nature of nanotechnology, a few strands of its development, and its economic contribution. Part III then examines the role of IP systems in nanotechnology's development, with a focus on patents and trade secrets. Part IV explores the nanotechnology innovation ecosystem more broadly, including the role of the state. Finally, Part V concludes that government intervention in the form of direct funding and IP incentives has played a key role in the development of nanotechnology, and argues against extrapolating too broadly from case studies that dismiss the effectiveness of these mechanisms.

10. Of course, the patent system itself is a product of the state, in which state-awarded exclusive rights are used to transfer supracompetitive returns from consumers to innovators. See Daniel J. Hemel & Lisa Larrimore Ouellette, *Beyond the Patents-Prizes Debate*, 92 TEX. L. REV. 303, 312–14, 371 (2013). But states play a more active role when choosing specific technologies to reward with public finances. See *id.* at 327–33 (contrasting the “market-set” reward of the patent system with “government-set” rewards from direct spending).

11. See *infra* notes 178–81 and accompanying text.

12. Amy Kapczynski, *Intellectual Property's Leviathan*, 77 LAW & CONTEMP. PROBS. 131, 131–32 (2014). Kapczynski doubts this characterization. *Id.* at 132.

13. Cf. MARIANA MAZZUCATO, *THE ENTREPRENEURIAL STATE: DEBUNKING PUBLIC VS. PRIVATE SECTOR MYTHS* 9 (2013) (arguing that contrary to the conventional wisdom, in practice the state is not a “bureaucratic machine” that merely fixes market failures, but rather an “entrepreneurial agent” and “lead risk taker”).

14. See *infra* Part IV.A.

II. NANOTECHNOLOGY'S DEVELOPMENT AND ECONOMIC CONTRIBUTION

Nanoscale particles are not new, but only in recent decades have scientists been able to truly visualize and control nanoscale phenomena. Nobel Prize-winning physicist Richard Feynman is often attributed with having first visualized the promise of manipulating matter at the nanoscale; he famously argued in 1959 that “there is plenty of room at the bottom” for applications such as nanoscale circuits and nanomedicine.¹⁵ Feynman’s vision gave rise to the field of nanotechnology, which is technology at the nanometer scale. Since then, 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.”¹⁶ 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.¹⁷ This Article synthesizes a broad literature on nanotechnology, and so the definitional ambiguity remains a necessary caveat.

Part II.A briefly reviews selected developments in nanotechnology with a focus on nanoelectronics. Part II.B then discusses nanotechnology’s transformative potential and attempts to quantify its significant economic contribution.

15. Richard Feynman, *There’s Plenty of Room at the Bottom*, Address Before the American Physical Society at Caltech (Dec. 29, 1959), in 23 *ENGINEERING & SCI.* 22, 22 (1960), <http://calteches.library.caltech.edu/1976/1/1960Bottom.pdf> [<http://perma.cc/R9YT-FGQC>].

16. SUBCOMM. ON NANOSCALE SCI., ENG’G & TECH., *THE NATIONAL NANOTECHNOLOGY INITIATIVE: SUPPLEMENT TO THE PRESIDENT’S 2015 BUDGET 3* (2014), http://www.whitehouse.gov/sites/default/files/microsites/ostp/NNI_FY15_Final.pdf [<http://perma.cc/62UB-V8PE>].

17. *See* OECD & U.S. NAT’L NANOTECHNOLOGY INITIATIVE, *SYMPOSIUM ON ASSESSING THE ECONOMIC IMPACT OF NANOTECHNOLOGY: SYNTHESIS REPORT 8* (2013), http://www.oecd.org/sti/nano/Washington%20Symposium%20Report_final.pdf [<http://perma.cc/K75Z-BUL8>] [hereinafter OECD].

A. Selected Developments in Nanotechnology

Nanotechnology, like most fields of innovation, depends 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.¹⁸ And a complete history of nanotechnology would not only describe all the foundational developments in physics, chemistry, biology, and engineering, but also extend across a vast range of applications today.¹⁹

By most accounts, the first consumer nanotechnology products involved passive nanoscale additives that were used to improve the properties of materials, such as those in tennis rackets, eyeglasses, and sunscreen.²⁰ 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; nanoparticles were often manufactured in bulk by chemical means by the mid-nineteenth century.²¹

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.²² Scientists have engineered these biomolecules and other nanomaterials for biological diagnostics and therapeutics, such as targeted drug delivery for cancer treatment.²³ As of 2013, a “couple hundred” nanotechnology-related medical therapies had been approved or had entered clinical trials in the United States.²⁴

18. See VLADIMIR MITIN ET AL., *QUANTUM MECHANICS FOR NANOSTRUCTURES* 1–2 (2010).

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

20. See, e.g., George A. Kimbrell, *Nanomaterial Consumer Products and FDA Regulation: Regulatory Challenges and Necessary Amendments*, 3 *NANOTECHNOLOGY L. & BUS.* 329, 331 (2006). Verifying the precise technology behind these claims, however, is often difficult. See Jerney N.A. Matthews, *Taking Stock of the Nanotechnology Consumer Products Market*, *PHYSICS TODAY*, Feb. 2014, at 22, 23.

21. See MITIN ET AL., *supra* note 18, at 1; JEREMY J. RAMSDEN, *NANOTECHNOLOGY* 9 (2011); *Nanotechnology Timeline*, NAT’L NANOTECHNOLOGY INITIATIVE, <http://nano.gov/timeline> [<http://perma.cc/EY3E-W2L6>].

22. Hashim Uddin Ahmed et al., *Nanotechnology for the Urologist*, in *HANDBOOK OF NANOPHYSICS: NANOMEDICINE AND NANOROBOTICS* 21-1 (Klaus D. Sattler ed., 2010).

23. See, e.g., *THE NANOBIO TECHNOLOGY HANDBOOK* 519 (Yubing Xie ed., 2013); Priyambada Parhi et al., *Nanotechnology-Based Combinational Drug Delivery: An Emerging Approach for Cancer Therapy*, 17 *DRUG DISCOVERY TODAY* 1044, 1044 (2012).

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

In some ways nanotechnology resembles prior “general purpose technologies” — such as the combustion engine, electricity, and the computer — that were at the center of prior periods of rapid development, in that nanotechnology development occurs across technology spaces.²⁵ Rather than describing the full history and breadth of nanotechnology research and development, this Article focuses on three strands of R&D from the perspective of nanoelectronics: (1) electron microscopy 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 because of their unparalleled electronic and mechanical properties for their size; and (3) commercial nanoelectronics, from transistors to magnetic memory, which have already had a significant market impact.²⁶ These brief histories reveal a web of intertwined academic and industrial research.

1. Research Tools: Seeing at the Nanoscale

The ability to visualize nanoscale structures has been critical to the development of nanotechnology. Nanoscale features are smaller than the wavelength of light and thus cannot be seen with optical microscopes;²⁷ however, they can be imaged with electrons, which have a much smaller wavelength.²⁸ Electrons can be transmitted through a thin sample (in a transmission electronic microscope, or “TEM”); projected in a focused beam across a surface (in a scanning electron microscope, or “SEM”); or both (in a scanning transmission electron microscope, or “STEM”). All three microscopes are key research tools for nanotechnology to this day,²⁹ and their development illustrates the pervasive intertwining of public and private incentives throughout the history of nanotechnology.

Images from the first functional TEM were published in 1932 by Max Knoll and his Ph.D. student Ernst Ruska at the Technical

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

26. See *infra* notes 51, 55–57, 63–64, 71, 74, 77 and accompanying text.

27. See RAMSDEN, *supra* note 21, at 5. But 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> [<http://perma.cc/D4TW-D8XU>] (discussing advances that have challenged the resolution limits of optical microscopy).

28. The 1929 Nobel Prize in Physics was awarded to Louis de Broglie for discovering the wave nature of electrons. *The Nobel Prize in Physics 1929*, NOBELPRIZE.ORG, http://www.nobelprize.org/nobel_prizes/physics/laureates/1929 [<http://perma.cc/8STK-X29E>].

29. For an overview from an electron microscope manufacturer, see generally FEI Co., AN INTRODUCTION TO ELECTRON MICROSCOPY (2010), http://www.nanolab.ucla.edu/pdf/Introduction_to_EM_booklet_July_10.pdf [<http://perma.cc/9M4Y-8ZCX>].

University of Berlin,³⁰ for which Ruska later shared the Nobel Prize.³¹ Ruska joined the German firm Siemens in 1936,³² which began successful commercial production three years later.³³

In 1935, Knoll published the first images made by *scanning* an electron beam in a precursor to the SEM.³⁴ Siemens researcher Manfred von Ardenne actually obtained SEM images in 1933, although these appeared only in a patent application and were not published.³⁵ (He did, however, publish images in 1938 from a related device, the first STEM.³⁶) Due to early commercial failures, little additional work on SEMs occurred until Charles Oatley and his engineering Ph.D. students at Cambridge University began researching SEM technology in 1948.³⁷ One of Oatley's graduates was instrumental in developing the first commercial SEM in 1965,³⁸ just as Ruska had helped move TEM technology from academic prototype to commercial production three decades earlier. The Japanese firm JEOL soon began marketing a competing product based on Oatley's design.³⁹

STEM technology was slower to progress: After von Ardenne's STEM was destroyed in 1944 in a World War II air raid on Berlin, a STEM was not developed again until physicist Albert Crewe created

30. DAVID B. WILLIAMS & C. BARRY CARTER, *The Transmission Electron Microscope*, in TRANSMISSION ELECTRON MICROSCOPY 4 (2d ed. 2009); C.T.K.-H. STADTLÄNDER, *Scanning Electron Microscopy and Transmission Electron Microscopy of Mollicutes*, in MODERN RESEARCH AND EDUCATIONAL TOPICS IN MICROSCOPY 122 (A. Méndez-Vilas & J. Díaz eds., 2007).

31. Press Release, Royal Swedish Acad. of Scis., The Nobel Prize in Physics 1986 (Oct. 15, 1986), http://www.nobelprize.org/nobel_prizes/physics/laureates/1986/press.html [<http://perma.cc/HG9J-EMME>].

32. 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 [<http://perma.cc/SDK2-TVBT>].

33. See WILLIAMS & CARTER, *supra* note 30, at 4. 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 over a German application filed on May 30, 1931).

34. McMullan, *supra* note 32, at 3–4. An earlier description of a microscope with a scanning electron beam can be found in 1929 German patents held by Hugo Stintzing of Giessen University; however, 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.

35. Stephen J. Pennycook, *A Scan Through the History of STEM*, in SCANNING TRANSMISSION ELECTRON MICROSCOPY 1–2 (Stephen J. Pennycook & Peter D. Nellist eds., 2011).

36. See McMullan, *supra* note 32, at 5, 8–10; Pennycook, *supra* note 35, at 1.

37. See McMullan, *supra* note 32, at 12; Oliver C. Wells & David C. Joy, *The Early History and Future of the SEM*, 38 SURFACE & INTERFACE ANALYSIS 1738, 1738 (2006).

38. See McMullan, *supra* note 32, at 20.

39. See *id.* at 20–21 (describing the sale to the Canadian firm and the introduction of JEOL's product); Wells & Joy, *supra* note 37, at 1739 (reporting that the SEM sold to Canada was the basis for JEOL's product).

one at the University of Chicago over two decades later.⁴⁰ A British firm then began commercial production that ceased in 1996, after which a professor at the University of Illinois worked with JEOL to convert one of their microscopes into a STEM with atomic-resolution capacity.⁴¹ As more manufacturers entered the market, the number of atomic-resolution STEMs doubled within a few years.⁴² Today, most TEM and STEM instruments are capable of a spatial resolution approaching 0.13 nanometers for thin samples.⁴³

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.⁴⁴ 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).⁴⁵ 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.⁴⁶

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.⁴⁷ 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.⁴⁸ Both instruments are now “routine tools” for investigating nanoscale materials with atomic resolution.⁴⁹

The development of the fundamental nanotechnology research tools discussed in this Section is in many ways very conventional: Universities played a key role in conducting basic research, and private sector companies were instrumental in commercializing these innovations, which were often patented. But it is worth remembering that this story became conventional for a reason: it often *does* work. Additionally, examining these technologies in detail helps bring out

40. See Pennycook, *supra* note 35, at 3, 6–7. In 1970, Crewe reported the first observations of single atoms using an electron microscope. *Id.* at 7.

41. *Id.* at 40.

42. *Id.*

43. WORLD TECH. EVALUATION CTR., *supra* note 19, at 77.

44. See BERT VOIGTLÄNDER, SCANNING PROBE MICROSCOPY: ATOMIC FORCE MICROSCOPY AND SCANNING TUNNELING MICROSCOPY 4–10 (2015).

45. Press Release, Royal Swedish Acad. of Scis., *supra* note 31.

46. 2010 Kavli Prize Laureates in Nanoscience, KAVLI PRIZE (June 3, 2010), <http://www.kavliprize.org/prizes-and-laureates/prizes/2010-kavli-prize-laureates-nanoscience> [<http://perma.cc/NJ27-5GRB>].

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

48. See U.S. Patent No. 4,724,318 (filed Aug. 4, 1986); U.S. Patent No. 4,343,993 (filed Sept. 12, 1980).

49. See WORLD TECH. EVALUATION CTR., *supra* note 19, at 73–74.

an overlooked aspect of this story; namely, that human capital played a key role in facilitating technology transfer. Each of the microscopy tools described above was developed with the help of academics, including graduate students who later took positions in industry, a professor who worked with a company to develop the tool he needed, and academics who worked with an industry researcher during the researcher's sabbatical. The Article will return later to the role of the state in driving innovation through investments in human capital, but first, it will turn to the next strand of nanotechnology R&D: three nanomaterials that were discovered with the help of the research tools described above.

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 the three structures illustrated in Figure 1: (1) soccer-ball-like structures known as fullerenes; (2) cylinders known as carbon nanotubes; and (3) sheets known as graphene. All of these discoveries rested on pioneering basic research about the behavior of electrons in carbon — primarily conducted by government-funded academics — including the work in the 1960s through the 1980s for which Massachusetts Institute of Technology (“MIT”) physics professor Mildred S. Dresselhaus received the 2012 Kavli Prize in Nanoscience.⁵⁰ Due to the unique nature of the carbon-carbon bond, all three structures have mechanical and electronic properties that rival or exceed the best known alternatives, as discussed below.

50. 2012 Kavli Prize Laureates in Nanoscience, KAVLI PRIZE (May 31, 2012), <http://www.kavliprize.org/prizes-and-laureates/prizes/2012-kavli-prize-laureates-nanoscience> [<http://perma.cc/3HDZ-SUSR>]. Dresselhaus's papers from that period indicate that her work was supported by grants from U.S. agencies. See, e.g., M.S. Dresselhaus et al., *Graphite Intercalation Compounds: Electronic Properties in the Dilute Limit*, 15 PHYSICAL REV. B 3180, 3191 (1977); S.J. Williamson et al., *De Haas-van Alphen Effect in Pyrolytic and Single-Crystal Graphite*, 140 PHYSICAL REV. A1429, A1429 (1965). On the scale of government funding for U.S. academics, see *infra* notes 229–30 and accompanying text.

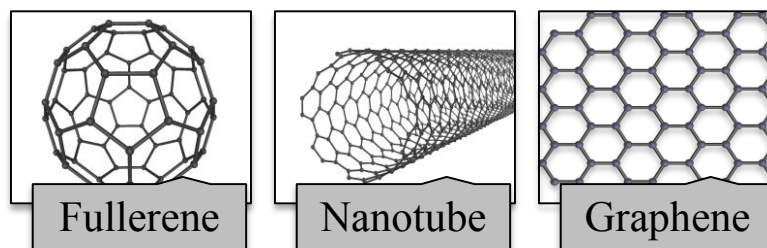


Figure 1: Carbon Nanostructures

A. Fullerenes

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.⁵¹ 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.⁵² This advance led to an explosion in fullerene-related patenting by entities that saw commercially viable opportunities, including by academics such as Smalley,⁵³ and by corporations, such as Sanofi-Aventis.⁵⁴ Fullerenes have been used commercially to enhance the strength of tools and sporting equipment⁵⁵ and add anti-wrinkle properties to cosmetics.⁵⁶ Their most promising applications, however, are

51. Press Release, Royal Swedish Acad. of Scis, The Nobel Prize in Chemistry 1996 (Oct. 9, 1996), http://www.nobelprize.org/nobel_prizes/chemistry/laureates/1996/press.html [<http://perma.cc/U5RQ-G46F>]. Their research was supported by grants from federal agencies in the United States and by the Welch Foundation, a nonprofit funder of basic chemical research. H.W. Kroto et al., *C60: Buckminsterfullerene*, 318 NATURE 162, 163 (1985).

52. W. Krätschmer et al., *Solid C60: A New Form of Carbon*, 347 NATURE 354, 354 (1990).

53. See, e.g., U.S. Patent No. 5,556,517 (filed June 7, 1995); U.S. Patent No. 5,591,312 (filed May 15, 1995); U.S. Patent No. 5,300,203 (filed Nov. 27, 1991); U.S. Patent No. 5,227,038 (filed Oct. 4, 1991).

54. See Richard Michalitsch et al., *The Fullerene Patent Landscape in Europe*, 5 NANOTECHNOLOGY L. & BUS. 85, 90, 92 (2008).

55. See, e.g., *Yonex Adds Fullerene to Badminton Rackets to Satisfy Hard Hitters*, NIKKEI TECHNOLOGY (Apr. 4, 2005), http://techon.nikkeibp.co.jp/english/NEWS_EN/20050404/103378 [<http://perma.cc/63NF-QQPC>] (describing the introduction of a company's second badminton racket in which fullerenes make "the racket lighter as well as stronger").

56. See *The Science Behind Nova C60*, NOVA C60, <http://www.novac60.com/innovation> [<http://perma.cc/2FNE-AXDH>] (touting the antioxidant properties of a commercial fullerene-based cosmetic product); see generally Shinya Kato et al., *Clinical Evaluation of Fullerene-C60 Dissolved in Squalane for Anti-Wrinkle Cosmetics*, 10 J. NANOSCIENCE & NANOTECHNOLOGY 6769 (2010) (presenting results of a clinical study of a fullerene-based product for wrinkle care).

in organic electronics (including solar cells) and bioscience (including drug delivery mechanisms).⁵⁷

B. Carbon Nanotubes

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 have been rediscovered a number of times since then.⁵⁸ 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 Sumio Iijima and Toshinari Ichihashi of NEC Corporation in Japan⁵⁹ and by Bethune et al. of IBM in California.⁶⁰ Since then, interest in nanotubes has surged.⁶¹ From 2001 to 2010, the U.S. National Science Foundation awarded 1142 grants related to carbon nanotubes, with an average award amount of \$338,398 — making nanotubes the second most heavily funded area of nanotechnology after thin films.⁶²

Carbon nanotubes are extremely strong, very good at dissipating heat, and high performing as either metals (tiny wires) or semiconductors (transistors or sensors), indicating “huge potential for nanoelectronics.”⁶³ For example, due to their ability to operate underwater, carbon nanotubes have been used to make electronic sensors for a variety of chemicals and biomolecules.⁶⁴ Like carbon fullerenes, dis-

57. Cf. Michael D. Diener, *Fullerenes for Photovoltaic and Bioscience Applications*, SIGMA-ALDRICH, <http://www.sigmaaldrich.com/materials-science/nanomaterials/fullerenes.html> [http://perma.cc/49CW-JJR3].

58. See generally Marc Monthieux & Vladimir L. Kuznetsov, *Who Should Be Given the Credit for the Discovery of Carbon Nanotubes?*, 44 CARBON 1621 (2006).

59. Sumio Iijima & Toshinari Ichihashi, *Single-Shell Carbon Nanotubes of 1-nm Diameter*, 363 NATURE 603, 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> [http://perma.cc/HP5A-B33J].

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

61. 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).

62. 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, 1965 tbl.12 (2013).

63. M.S. Dresselhaus et al., *Electronic, Thermal and Mechanical Properties of Carbon Nanotubes*, 362 PHIL. TRANSACTIONS ROYAL SOC'Y LONDON A 2065, 2092 (2004).

64. See K. Rajavel et al., *Recent Progress on the Synthesis and Applications of Carbon Based Nanostructures*, 6 RECENT PATS. ON NANOTECHNOLOGY 1, 3 (2012). See generally Lisa Larrimore Ouellette, *Chemical and Biological Sensing with Carbon Nanotubes in Solution* (Jan. 2008) (unpublished Ph.D. dissertation, Cornell University), http://www.lassp.cornell.edu/lassp_data/mceuen/homepage/Publications/Thesis_Larrimore.pdf [http://perma.cc/LK7F-HZW9].

persed carbon nanotubes are already used in diverse commercial products, including thin-film electronics.⁶⁵ But the most promising applications — those that take advantage of the electrical properties of *individual* nanotubes — are still a few years away from the commercial stage.⁶⁶ For example, IBM predicts that it will have commercial carbon-nanotube-based transistors ready by 2020.⁶⁷

C. Graphene

Graphene, the newest carbon-based nanomaterial of interest, was described theoretically in 1947 by P.R. Wallace,⁶⁸ 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.⁶⁹ In 2005, they published electrical measurements on a single graphene layer,⁷⁰ and in 2010, Geim and Novoselov won the Nobel Prize for their graphene work.⁷¹ Unlike the Smalley group at Rice, the Geim group at Manchester has shown little interest in patenting their discoveries,⁷² though the overall patent landscape shows an explosion of interest in the material.⁷³ Graphene has potential applications ranging from electronics to biosensing,⁷⁴ but signifi-

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

66. See *id.* at 537.

67. Tom Simonite, *IBM: Commercial Nanotube Transistors Are Coming Soon*, MIT TECH. REV. (July 1, 2014), <http://www.technologyreview.com/news/528601/ibm-commercial-nanotube-transistors-are-coming-soon> [<http://perma.cc/SK7E-FCWC>].

68. See generally P.R. Wallace, *The Band Theory of Graphite*, 71 PHYSICAL REV. 622 (1947).

69. See K.S. Novoselov et al., *Electric Field Effect in Atomically Thin Carbon Films*, 306 SCIENCE 666, 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), <http://www.newyorker.com/magazine/2014/12/22/material-question> [<http://perma.cc/Z8U7-YDPC>].

70. K.S. Novoselov et al., *Two-Dimensional Atomic Crystals*, 102 PROC. NAT’L ACAD. SCIS. 10451, 10451 (2005).

71. See ROYAL SWEDISH ACAD. OF SCIS., SCIENTIFIC BACKGROUND ON THE NOBEL PRIZE IN PHYSICS 2010: GRAPHENE 1 (2010), http://www.nobelprize.org/nobel_prizes/physics/laureates/2010/advanced-physicsprize2010.pdf [<http://perma.cc/UTP6-3W5A>].

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

73. 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. U.K. INTELLECTUAL PROP. OFFICE, GRAPHENE: THE WORLDWIDE PATENT LANDSCAPE IN 2013, 2–4 (Mar. 11, 2013), <https://www.gov.uk/government/publications/graphene> [<https://perma.cc/H6ZK-4FG7>]. For another look at the graphene patent landscape, see generally Chinh H. Pham & Roman Fayerberg, *Current Trends in Patenting Graphene and Graphene-Based Inventions*, 8 NANOTECHNOLOGY L. & BUS. 10 (2011).

74. 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

cant hurdles remain for implementation.⁷⁵ 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.”⁷⁶

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. As of 2010, about sixty percent of the U.S. semiconductor market — which has a market value of about \$90 billion — utilized nanoscale features.⁷⁷ Intel has since introduced commercial chips with 14-nanometer transistors.⁷⁸ One nanotechnology review recently argued that “[t]he miniaturization of computing and information storage is the most important technological development of the last half century,” with computers now able to “perform as many operations in a second as a human can have thoughts in a lifetime”; every year we create enough new digital information to represent “the equivalent of a hundred thousand books . . . for every man, woman, and child on the planet.”⁷⁹

The steady shrinking of device size that has enabled this information revolution 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.⁸⁰ To shrink devices below one hundred 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 the creation of ever-smaller

NANOMATERIALS (2014). For a recent report of a graphene vapor sensor, see generally Girish S. Kulkarni et al., *Graphene Nanoelectric Heterodyne Sensor for Rapid and Sensitive Vapour Detection*, 5 NATURE COMM. 4376 (2014).

75. See Colapinto, *supra* note 69.

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

77. WORLD TECH. EVALUATION CTR., *supra* note 19, at 6 fig.3, 7 tbl.2.

78. Leo Kelion, *Intel Launches First 14-Nanometre Processor for Thin Fanless PCs*, BBC NEWS (Sept. 5, 2014), <http://www.bbc.com/news/technology-29066210> [<http://perma.cc/FMM8-TVTR>].

79. Paul L. McEuen, *Small Machines*, DÆDALUS, Summer 2012, at 35, 36. McEuen predicts that the revolution that occurred in the semiconductor industry in the 1960s — machines that can “build copies of themselves from raw materials” and “change and evolve” — is now occurring in the area of “nanomachines,” a phenomenon he expects to be “pervasive” in fifty years. *Id.* at 44.

80. WORLD TECH. EVALUATION CTR., *supra* note 19, at 377.

features.⁸¹ These advances depended on basic improvements in nanofabrication and characterization that took place during the prior decade, and “[c]ontinued scaling will require further fundamental advances,”⁸² perhaps involving carbon nanotubes or graphene.⁸³

B. Nanotechnology’s Economic Contribution

The brief snapshot of some developments in nanotechnology provided above gives a sense of how certain strands of nanotechnology innovation have progressed, but it does not illustrate the broader economic contribution provided by these new technologies. The remainder of this Part 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 impacted areas ranging from drug delivery to electronics to materials science. Additionally, nanotechnology has been compared to prior general-purpose technologies because it is an enabling tool across many fields rather than just a single field. At a 2013 forum convened by the U.S. Government Accountability Office, with participants selected by the National Academies, multiple participants suggested that nanomanufacturing had the potential to transform society as significantly as innovations such as electricity, computers, and the Internet.⁸⁴ For example, researchers thought nanomanufacturing would “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.”⁸⁵ There are potential applications across a huge range of sectors, from improved battery-powered vehicles, to more precisely targeted medical therapies, to nanotube-enhanced pavement with remote sensing capabilities.⁸⁶

In addition to opening new markets and fostering economic growth, nanotechnology also has the potential to enhance social welfare by addressing global sustainability challenges. Researchers have made significant progress in developing nanotechnology-based solu-

81. *Id.* at 378.

82. *Id.*

83. *See id.* at 378, 381–82, 399–403.

84. U.S. GOV’T ACCOUNTABILITY OFF., GAO-14-181SP, NANOMANUFACTURING: EMERGENCE AND IMPLICATIONS FOR U.S. COMPETITIVENESS, THE ENVIRONMENT, AND HUMAN HEALTH 13 (2014), <http://www.gao.gov/assets/670/660591.pdf> [<http://perma.cc/FJ7C-3FQK>].

85. *Id.* at 13, 15.

86. *See id.* at 14.

tions for water treatment, desalination, and re-use, and nanotechnology has the potential to continue providing more efficient and cost-effective solutions.⁸⁷ Nanotechnology researchers have also improved food safety and biosecurity, produced lightweight, strong nanocomposites for building more fuel-efficient vehicles, created methods for separating carbon dioxide from other gases, and dramatically improved the efficiency of plastic solar cells.⁸⁸ The ability to shape the world at the nanoscale presents truly amazing possibilities.

2. Quantitative Estimates of the Nanotechnology Market

Assessing the total economic impact of all developments in nanotechnology is challenging. The Organization for Economic Cooperation and Development (“OECD”) and the U.S. National Nanotechnology Initiative (“NNI”) held a 2012 symposium focused on addressing the difficulties of this assessment, although it raised more questions than it answered.⁸⁹ 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.”⁹⁰

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 or technology transfer awards for small businesses; and long-term outcomes, such as nanotechnology companies, jobs, products, and sales.⁹¹ 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 “trace backward from an outcome of significance.”⁹² 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. It is worth keeping in mind, however, that social benefit is not always captured by market value.⁹³ Some countries are looking to other ways to value the social

87. See WORLD TECH. EVALUATION CTR., *supra* note 19, at 160.

88. See *id.* at 161, 171, 214.

89. See OECD, *supra* note 17, at 16–19.

90. See *id.* at 8–10.

91. See NAT’L RESEARCH COUNCIL, TRIENNIAL REVIEW OF THE NATIONAL NANOTECHNOLOGY INITIATIVE 65–66 (2013), http://www.nap.edu/openbook.php?record_id=18271 [<http://perma.cc/N2H3-WWRD>].

92. OECD, *supra* note 17, at 68.

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

benefit of nanotechnology. 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.⁹⁴

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, how much worth should be attributed to nanotechnology in markets for semiconductors and electronics, which are valued at over \$200 billion and \$1 trillion, respectively, given that modern semiconductors are built in the nanoscale range?⁹⁵

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 the value that nanotechnology adds.⁹⁶ Based on this method, the value added to the UK economy by some nanotechnology-enabled products was “quite modest,”⁹⁷ although the specific products and measured value were not reported. The U.S. STAR METRICS program takes a different approach to measuring the impact of government R&D investments by attempting to link inputs to outputs and outcomes.⁹⁸ 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 broadly to extend the nanotechnology umbrella. A few countries have adopted their own classification systems. For example, the Russian Federation has surveyed businesses about nanotechnology-enabled goods and services since 2010 and estimates overall nanotechnology-related sales in Russia at \$6 billion per year.⁹⁹ But there are no uniform global standards for nanotechnology classification.

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 nano-

94. OECD, *supra* note 17, at 52.

95. *Id.* at 61.

96. Katherine Bojczuk & Ben Walsh, *Models, Tools and Metrics Available to Assess the Economic Impact of Nanotechnology* 9–10 (OECD/NNI Int’l Symposium on Assessing the Econ. Impact of Nanotechnology, Background Paper No. 4, 2012), <http://www.oecd.org/sti/nano/49932079.pdf> [<http://perma.cc/FL6U-WPFM>].

97. OECD, *supra* note 17, at 47.

98. 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> [<https://perma.cc/Z8AH-NBDP>].

99. OECD, *supra* note 17, at 44–45.

tech . . . grew from \$339 billion in 2010 to \$731 billion in 2012.”¹⁰⁰ 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.¹⁰¹ 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.¹⁰² 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 2013.¹⁰³ But a different report from BCC Research estimated the nanomedicine market alone at \$50.1 billion in 2011,¹⁰⁴ calling the consistency of their methodology into question.

Mihail Roco, 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. Roco has summarized the key indicators of nanotechnology development in 2000 and 2010 as follows:

100. LUX RESEARCH INC., NANOTECHNOLOGY UPDATE: CORPORATIONS UP THEIR SPENDING AS REVENUES FOR NANO-ENABLED PRODUCTS INCREASE 2 (2014) [hereinafter NANOTECHNOLOGY UPDATE].

101. Lux Research has a disclaimer, writing 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), http://www.nsf.gov/news/news_summ.jsp?cntn_id=130586 [<http://perma.cc/H5FZ-CJ89>] (reporting that National Science Foundation and National Nanotechnology Initiative-funded independent study identified more than \$1 trillion in global revenue from nano-enabled products in 2013).

102. 1 LUX RESEARCH INC., THE NANOTECH REPORT 1–3 (5th ed. 2007).

103. *See* BCC Research, *Nanotechnology: A Realistic Market Assessment*, BCC RESEARCH (Nov. 2014), <http://www.bccresearch.com/market-research/nanotechnology/nanotechnology-market-assessment-report-nan031f.html> [perma.cc/72UK-YPL5].

104. BCC Research, *Nanotechnology in Medical Applications: The Global Market*, BCC RESEARCH (Jan. 2012), <http://www.bccresearch.com/market-research/healthcare/nanotechnology-medical-applications-global-market-hlc069b.html> [perma.cc/WB3B-VWGB].

Table 1: Indicators of Nanotechnology Development¹⁰⁵

	2000	2010
People in Primary Workforce	60,000	600,000
Papers in SCI-Indexed Journals	18,085	78,842
Patent Applications	1197	20,000
Market Value of Final Products	\$30 billion	\$300 billion
Public & Private R&D Funding	\$1.2 billion	\$18 billion
Venture Capital	\$0.21 billion	\$1.3 billion

III. IP AND NANOTECHNOLOGY

Assessing the net impact of IP, or its efficacy relative to other innovation incentives, has proven difficult,¹⁰⁶ 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 recognize 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.¹⁰⁷ This Part will focus, however,

105. 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. Email from Mihail C. Roco, Senior Advisor for Nanotechnology, Nat'l Sci. Found., to Lisa Larrimore Ouellette, Assistant Professor of Law, Stanford Univ. (Jan. 8, 2015, 07:57 PST) (on file with author).

106. See generally Ouellette, *supra* note 4 (reviewing the literature on how to assess the impact of IP on innovation).

107. This Part focuses on patents and trade secrets, but there are also nanotechnology-related issues in trademark and copyright law. Trademarks are important for protecting an innovator's first-mover advantage. 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. See generally 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 2006 hospitalization of German consumers who used the bathroom cleaner MAGIC NANO led to public outcry in the United States 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. There also have been some creative examples of nanoscale art, see, for example, Bill Steele, *To Dramatize Nanotechnology, Cornell Gives President Clinton the World's Smallest Saxophone*, CORNELL CHRON. (July 12, 2000), <http://www.news.cornell.edu/stories/2000/07/cornell-gives-clinton-nanosaxophone> [<http://perma.cc/82X4-MVDY>], including imitations of macroscale art that raise questions of copyright law, see, for example, 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> [<http://perma.cc/8MUL-5KNV>].

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 trade secrets are used for appropriation, although their importance varies significantly by sector.¹⁰⁸

A. Patents

Nanotechnology differs from many other important fields of invention in that many of its foundational inventions were patented at the outset, and many of those patents were issued to universities.¹⁰⁹ By 2012, over 30,000 nanotechnology patents had been granted by the U.S. Patent & Trademark Office (“USPTO”) alone.¹¹⁰ 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.¹¹¹ While there have been some concerns about potential limitations on the patentability of nanotechnology, as discussed in the following Section, many more commentators have expressed the opposite concern that there are too many nanotechnology patents, which will lead to inefficient patent thickets.

1. Potential Limitations on the Patentability of Nanotechnology

Although the Agreement on Trade-Related Aspects of Intellectual Property Rights (“TRIPS”) outlines patents for “any inventions . . . in all fields of technology,” it allows exceptions that implicate some nanotechnology inventions, including exceptions for medical diagnostic methods and for inventions that could endanger health or the environment.¹¹² Additionally, some countries have limited what counts as

108. See Wesley M. Cohen et al., *Protecting Their Intellectual Assets: Appropriability Conditions and Why U.S. Manufacturing Firms Patent (or Not)* 1 (Nat’l Bureau of Econ. Research, Working Paper 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*, 18 BROOKINGS PAPERS ON ECON. ACTIVITY, no. 3, 1987, at 783, 818, 824 (surveying 650 industry research managers and finding that the pharmaceutical industry is one of the few industries where patents were rated more effective than other means of appropriation).

109. See Lemley, *supra* note 9, at 616.

110. Chen et al., *supra* note 62, at 5 tbl.2.

111. 1 LUX RESEARCH INC., *supra* note 102, at 201.

112. Agreement on Trade-Related Aspects of Intellectual Property Rights art. 27, Apr. 15, 1994, Marrakesh Agreement Establishing the World Trade Organization, Annex 1C, 108 Stat. 4809, 1869 U.N.T.S. 331 [hereinafter TRIPS Agreement].

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 form),¹¹³ as well as any “law of nature,” such as a method for calibrating the proper dosage of a drug.¹¹⁴

These expansive patentable subject matter exceptions raise questions about the validity of many nanotechnology patents in the United States.¹¹⁵ Many nanomaterials exist in nature; for example, carbon-based nanoparticles are produced by common candle flames,¹¹⁶ and graphene is produced simply by writing with a pencil.¹¹⁷ 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. This could become a concern for patentees who later seek to assert their patents.

Nanotechnology inventions might also be found unpatentable for lack of novelty (1) if the invention was “inherent” in the prior art (as would be the case for attempts to patent the inadvertent uses of nanoscale particles mentioned in Part II.A); or (2) if they are merely nanoscale formulations of previously disclosed compounds.¹¹⁸ 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.¹¹⁹ Similarly, the TBA held in *SmithKline Beecham Biologicals v. Wyeth Holdings Corporation* that a patent application

113. *Ass’n for Molecular Pathology v. Myriad Genetics, Inc.*, 133 S. Ct. 2107, 2111, 2116 (2013).

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

115. *See generally* 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) (examining whether and to what extent recent Supreme Court decisions will impact nanotechnology patentability).

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

117. *See* P. Blake et al., *Making Graphene Visible*, 91 APPLIED PHYSICS LETTERS 063124-1, 063124-1 (2007).

118. *See* PRABUDDHA GANGULI & SIDDHARTH JABADE, NANOTECHNOLOGY INTELLECTUAL PROPERTY RIGHTS: RESEARCH, DESIGN, AND COMMERCIALIZATION 28 (Gabor L. Hornyak ed., 2012).

119. *Id.*

on a vaccine agent with 80–500 nanometer particles did not destroy the novelty of an agent with 60–120 nanometer particles.¹²⁰

Finally, even a novel invention could be unpatentable for lack of an “inventive step” (known as obviousness in the United States).¹²¹ 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.”¹²² As discussed in Part II, nanotechnology does not involve a “mere change” in size — most nanotechnology definitions require that the size confer novel properties. There is no evidence that this has been a significant barrier to patentability generally.¹²³ However, one group of U.S. patent lawyers 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 advised nanotechnology patent applicants to focus on elements of their invention other than its reduction in size.¹²⁴

2. Knowledge Diffusion Through Patent Disclosure

Under TRIPS, patentees must “disclose [their] invention in a manner sufficiently clear and complete for the invention to be carried out by a person skilled in the art.”¹²⁵ Other researchers can then read these disclosures to learn about the patented technologies; patent citation and co-authorship networks are regularly used to model knowledge diffusion, including in nanotechnology.¹²⁶

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.¹²⁷ Out of 211 researchers (primarily in the United States), 64% reported that they have read patents, and 60% of those reading

120. *Id.* at 28–29.

121. TRIPS requires an “inventive step” in order for inventions to be patentable. TRIPS Agreement, *supra* note 112, 1869 U.N.T.S. at 331. This requirement is codified in the U.S. Patent Act. *See* 35 U.S.C. § 103 (2012).

122. Application of Troiel, 274 F.2d 944, 949 (C.C.P.A. 1960) (citations omitted).

123. 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, 1334 (Fed. Cir. 2012) (rejecting patent application because it was an obvious combination of existing inventions).

124. Ronald A. Bleeker et al., *Patenting Nanotechnology*, MATERIALS TODAY, Feb. 2004, at 44, 48.

125. TRIPS Agreement, *supra* note 112, 1869 U.N.T.S. at 332.

126. *See, e.g.,* 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. 1017, 1018–19 (2015).

127. *See* Lisa Larrimore Ouellette, *Do Patents Disclose Useful Information?*, 25 HARV. J.L. & TECH. 545, 547 (2012).

patents for scientific reasons (rather than legal reasons) said they found useful technical information in patents.¹²⁸ Respondents reported that patents can show “how a particular device works,” can “put the ideas and research in context and offer[] some plausible views as to” the respondents’ own research, and can keep “you from going down a road that has already been traveled.”¹²⁹ Others stated that often “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.”¹³⁰

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:

[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”).¹³¹

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.¹³² This finding raises questions about how well the enablement requirement is 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 (1) better enforcement of current disclosure requirements (such as through examiner training and peer review); (2) faster patent

128. *Id.* at 548.

129. *Id.* at 575.

130. *Id.*

131. *Id.* at 575–76.

132. *Id.* at 606.

publication (especially for patentees such as universities that have little need for secrecy); (3) improved access to the patent literature through search and annotation tools; and (4) incentives to cite relevant patents in scientific publications.¹³³

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.¹³⁴ But as discussed below, it is not evident that there is in fact a patent thicket problem in nanotechnology.

3. Patent Thickets and Patent Litigation

Commentators have raised concerns about potential nanotechnology patent thickets since at least 2004.¹³⁵ 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.¹³⁶ But despite these concerns, there is little evidence of an actual patent thicket problem 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 ambiguous patent claim terms such as "nanocomposite"¹³⁷ and "nanoparticles."¹³⁸ In one high-profile case, Elan Pharmaceuticals won a \$55 million jury verdict for reasonable

133. *See id.* at 585–601.

134. *See* J. Peter Paredes, *Written Description Requirement in Nanotechnology: Clearing a Patent Thicket?*, 88 J. PAT. & TRADEMARK OFF. SOC'Y 489, 493–94 (2006).

135. *See* Ted Sabety, *Nanotech Innovation and the Patent Thicket: Which IP Policies Promote Growth?*, 1 NANOTECHNOLOGY L. & BUS. 262, 263 (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, 701 (2007); Raj Bawa, *Will the Nanomedicine "Patent Land Grab" Thwart Commercialization?*, 1 NANOMEDICINE: NANOTECHNOLOGY, BIOLOGY, & MED. 346, 348 (2005); Douglas J. Sylvester & Diana M. Bowman, *Navigating the Patent Landscapes for Nanotechnology: English Gardens or Tangled Grounds?*, in BIOMEDICAL NANOTECHNOLOGY: METHODS AND PROTOCOLS 359, 359–60 (Sarah J. Hurst ed., 2011).

136. *See* Raj Bawa, *Nanotechnology Patenting in the US*, 1 NANOTECHNOLOGY L. & BUS. 31, 38 (2004); Vivek Koppikar et al., *Current Trends in Nanotech Patents: A View from Inside the Patent Office*, 1 NANOTECHNOLOGY L. & BUS. 24, 27 (2004).

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

138. *Cephalon, Inc. v. Celgene Corp.*, 985 F. Supp. 2d 171, 175 (D. Mass. 2013).

royalties based on its claim that the first nanoparticle-based cancer therapy drug, Abraxane, infringed two of its nanoparticle formulation patents.¹³⁹ 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 a plaintiff or defendant, but all of these cases appear to have settled.¹⁴⁰

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 later reached an agreement with the patent plaintiff and emerged from bankruptcy.¹⁴¹ In another case involving a licensing dispute, a court enjoined a German inventor from terminating a license agreement with Nano-Proprietary, a nanotechnology IP company.¹⁴² Nano-Proprietary bought an exclusive right to sublicense the inventor's patents on using carbon nanotubes as cathodes in displays, which it believed to have tremendous market potential, but was then unable to find any sub-licensees.¹⁴³ Investing in uncertain technologies is highly risky; in addition to having a more unpredictable return, these deals are broken and litigated more often than deals involving more mature technologies.

Prabuddha Ganguli and Siddharth Jabade profile a number of other patent disputes.¹⁴⁴ But these cases do not illustrate any thicket-related licensing difficulties. In fact, they do not seem qualitatively different from patent disputes involving other technologies. Nano-

139. See William F. Prendergast & Heather N. Schafer, *Nanocrystalline Pharmaceutical Patent Litigation: The First Case*, 5 NANOTECHNOLOGY L. & BUS. 157, 157 (2008). The parties then settled for a one-time fee of \$78 million. 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> [<http://perma.cc/T4BQ-9GHJ>].

140. See Lex Machina Party Search, LEX MACHINA, <https://law.lexmachina.com/party/> (search for cases in which "Nanometrics" is a party) (last visited Dec. 10, 2015). The resulting six cases were all coded as likely settlements. *Id.* For an over-inclusive search for other nanotechnology cases, see Lex Machina Search Results, LEX MACHINA, <https://lexmachina.com> (search for patent cases with keywords "nano* NOT nanosecond") (last visited Dec. 10, 2015) (resulting in 1068 cases, with 128 won on the merits by the patentee, 95 won by the accused infringer based on invalidity or noninfringement, 589 likely settled, and the remainder either resolved procedurally or still pending). While these numbers should not be used as a measure of all nanotechnology patent litigation, they provide a rough sense of the number of filed cases resulting in settlement.

141. GANGULI & JABADE, *supra* note 118, at 135.

142. *Nano-Proprietary, Inc. v. Keesmann*, No. 06 C 2689, 2007 WL 433100, at *1 (N.D. Ill. Jan. 30, 2007).

143. *Id.* at *2–3.

144. See GANGULI & JABADE, *supra* note 118, at 135–75.

technology patents may have problems such as large numbers of difficult-to-search patents,¹⁴⁵ slow time to issuance, imperfect screening at the patent office (particularly for disclosure requirements), and costly litigation, but these are problems that impact the patent system as a whole, not problems with the nanotechnology patent system in particular.

B. Trade Secrets

Trade secret law is also a key piece of the nanotechnology IP system. As noted above, nanotechnology research often 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.¹⁴⁶ Because the difficulty of reverse engineering nanotechnology inventions may often weigh in favor of secrecy over patenting, the number of nanotechnology patents likely understates corporate innovation in the field.¹⁴⁷

Lux Research's 2007 report noted, unsurprisingly, that nanotechnology process innovations are particularly likely to be protected by trade secrets.¹⁴⁸ Among nanomaterials producers, those focused on ceramic nanomaterials, nanostructured metals, and catalysts were most likely to rely on trade secrets.¹⁴⁹ Specific companies protecting their IP with trade secrets include Aspen Aerogels, a startup with a nanoporous silica aerogel product, and Cap-XX, a small-to-midsized firm focusing on nanoporous carbon supercapacitor electrodes for mobile devices.¹⁵⁰

There have already been significant trade secret disputes in the United States related to 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.¹⁵¹ The value of Montgomery's settlement payment to Nanogen is estimated to be about \$11 million.¹⁵² In another case, Agilent Tech-

145. For a pedagogical overview of how to look for nanotechnology prior art, see GANGULI & JABADE, *supra* note 118, at 67.

146. See PATRICK M. BOUCHER, NANOTECHNOLOGY: LEGAL ASPECTS 73–74 (Gabor L. Hornyak ed., 2008).

147. Lemley, *supra* note 9, at 617.

148. 1 LUX RESEARCH INC., *supra* note 102, at 268.

149. *Id.* at 65, 96, 127.

150. 2 LUX RESEARCH INC., THE NANOTECH REPORT 29, 47 (5th ed. 2007).

151. BOUCHER, *supra* note 146, at 76.

152. *Id.*

nologies received a \$4.5 million damages award after suing former employees for misappropriation of trade secrets related to liquid chromatography using nanoscale particles.¹⁵³

Allegations of trade secret theft are not always so successful. NanoMech sued former employee Arunya Suresh for violating a non-disclosure agreement.¹⁵⁴ 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.¹⁵⁵ The court concluded that the inevitable disclosure doctrine applied only to cases in which plaintiffs threatened misappropriation of trade secrets — and not to cases involving breach of contract claims — and so the court granted Suresh’s motion for judgment on the pleadings.¹⁵⁶

As in the patent litigation context, it is not clear that nanotechnology raises any special challenges in the trade secret context. To be sure, there are broader concerns with trade secret protection: Keeping knowledge secret rather than disclosing it in patent documents can impede its dissemination, and strong legal protections for trade secrets may not be worth the costs.¹⁵⁷ But these concerns are not specific to nanotechnology.

IV. THE NANOTECHNOLOGY INNOVATION ECOSYSTEM

Although IP has played an important role in nanotechnology research, there are many innovation incentives beyond IP. This Part examines the complex innovation ecosystem that has supported nanotechnology development. First, Part IV.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. Part IV.B then turns to the actors within this ecosystem, including national laboratories, universities, large corporations, and small startups. Finally, Part IV.C examines the mechanisms through which they interact. These subsets of the nanotechnology innovation ecosystem of course overlap, but viewing the

153. *Agilent Techs., Inc. v. Kirkland*, C.A. No. 3512-VCS, 2010 WL 610725, at *31 (Del. Ch. Feb. 18, 2010).

154. *NanoMech, Inc. v. Suresh*, No. 5:13-CV-05094, 2013 WL 4805692, at *1 (W.D. Ark. Sept. 9, 2013), *aff’d*, 777 F.3d 1020 (8th Cir. 2015).

155. *Id.* at *4–5.

156. *Id.* at *6–7.

157. See generally Robert G. Bone, *The (Still) Shaky Foundations of Trade Secret Law*, 92 TEX. L. REV. 1803 (2014). The counterargument is that trade secret law prevents companies from over-investing in secrecy to protect their information, such that it actually encourages disclosure. See Mark A. Lemley, *The Surprising Virtues of Treating Trade Secrets as IP Rights*, 61 STAN. L. REV. 311, 313 (2008).

system from each of these perspectives will provide a better understanding of the entire complex system.

A. State Support for Nanotechnology R&D

The state supports innovation in nanotechnology and other fields through a variety of policy levers. Many fields of law have a substantial impact on innovation, including tort law, immigration law, and antitrust law, to name a few.¹⁵⁸ Of particular relevance to nanotechnology are environmental and safety regulations, as many governments have debated how to address concerns about negative impacts of nanotechnology without stifling innovation in the field.¹⁵⁹ General investments in human capital, such as through education, are also critical. But the most obvious form of state support for nanotechnology — and the focus of this Section — is financial support for 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.¹⁶⁰

Governments facilitate financial transfers to innovators in four general forms: (1) direct R&D spending through grants and procurement contracts (including spending on national laboratories); (2) innovation prizes; (3) R&D tax incentives; and (4) various forms of intellectual property (including the patent-like reward of regulatory exclusivity).¹⁶¹ In theory, all of these incentives can accomplish the same goal. IP transfers reward innovators through supracompetitive prices on protected products or services while imposing an equivalent cost on society through taxing and spending, even though this transfer is not reflected in government budgets.¹⁶²

In practice, however, there are important differences in the efficacy of these transfer mechanisms. One distinction is whether governments tailor rewards on a project-by-project basis, or simply establish technology neutral ground rules. Tailored rewards, such as grants or

158. See generally THE KAUFFMAN TASK FORCE ON LAW, INNOVATION, AND GROWTH, RULES FOR GROWTH: PROMOTING INNOVATION AND GROWTH THROUGH LEGAL REFORM (2011), http://www.kauffman.org/~media/kauffman_org/research%20reports%20and%20covers/2011/02/rulesforgrowth.pdf [<http://perma.cc/RV2L-2ABY>].

159. For a detailed discussion of nanotechnology environmental, health, and safety issues, see WORLD TECH. EVALUATION CTR., *supra* note 19, at 159–206. When determining how to regulate nanotechnology, governments should be aware that the field could develop a polarizing political valence similar to other environmental and technological risks, such as global warming, nuclear power, and genetically modified foods. See *id.* at 239; Dan M. Kahan et al., *Cultural Cognition of the Risks and Benefits of Nanotechnology*, 4 NATURE NANOTECHNOLOGY 87 (2008).

160. See Hemel & Ouellette, *supra* note 93, at 310–15.

161. See *id.* at 314–26 (describing how these policies are implemented in the United States).

162. See *id.* at 312–14 (discussing how patents act as a “shadow tax”).

fixed prizes, are most effective when the government can foresee a potential invention and evaluate its costs and benefits. In contrast, technology neutral devices, such as patents and tax incentives, leverage private information about the value of potential projects.¹⁶³ 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 can provide a strong incentive to succeed; however, if a project's payoff is too delayed or speculative, ex ante rewards such as grants and tax credits may be the only effective form of incentive.¹⁶⁴

Part III examined the role of IP in nanotechnology's development, and it is important to remember that IP *is* a product of the state, even if the resulting transfer to innovators is off-budget. Tax incentives — the other major market-set reward for innovators — likely also play an important role, although calculating the nanotechnology-specific portion of this transfer is difficult. The two largest R&D tax incentives in the United States, §§ 41 and 174 of the Internal Revenue Code, cost over \$10 billion per year,¹⁶⁵ and worldwide, tens of billions of dollars are spent each year on R&D tax incentives.¹⁶⁶ In addition to these technology neutral incentives, at least six U.S. states have enacted nanotechnology-specific tax incentives,¹⁶⁷ and a federal nanotechnology tax incentive has been proposed.¹⁶⁸ Innovation prizes are also a growing policy choice in the United States,¹⁶⁹ and while they are not yet a major tool in the nanotechnology space, a federal nanotechnology prize has been proposed,¹⁷⁰ and private non-profit prizes already exist.¹⁷¹

163. *See id.* at 327–33.

164. *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.

165. 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).

166. *See* OECD, THE INTERNATIONAL EXPERIENCE WITH R&D TAX INCENTIVES 4 fig.1 (2011), <http://www.finance.senate.gov/imo/media/doc/OECD%20SFC%20Hearing%20testimony%209%2020%2011.pdf> [<http://perma.cc/59QQ-92QQ>].

167. *See* 35 ILL. COMP. STAT. 5/220 (2012); MINN. STAT. § 116J.8737 (2015); NEB. REV. STAT. § 77-6302 (2011); VA. CODE § 58.1-339.4 (2006); WIS. STAT. § 238.15 (2015). Arkansas enacted a nanotechnology research tax credit in 2001 but repealed it in 2009. *See* ARK. CODE ANN. § 15-4-2104 (2001); ARK. CODE ANN. § 15-4-2104 (2009) (repealing the 2001 legislation).

168. *See, e.g.*, Nanotechnology Advancement and New Opportunities Act of 2013, H.R. 394, 113th Cong. (2013); Nanotechnology Advancement and New Opportunities Act of 2011, H.R. 2749, 112th Cong. (2011); Nanotechnology Advancement and New Opportunities Act of 2009, H.R. 820, 111th Cong. (2009); Nanotechnology Advancement and New Opportunities Act of 2007, H.R. 3235, 110th Cong. (2007).

169. *See* Hemel & Ouellette, *supra* note 93, at 317–19.

170. *See, e.g.*, Nanotechnology Innovation and Prize Competition Act of 2009, S. 596, 111th Cong. (2009); Nanotechnology Innovation and Prize Competition Act of 2008, H.R.

Therefore, most nanotechnology-specific state support — both for basic research and for early stage commercialization projects — currently comes in the form of direct grants from sources such as grant organizations, national laboratories, and procurement contracts. Internationally, over sixty countries created national nanotechnology R&D programs between 2001 and 2004.¹⁷² The first and largest program is the U.S. NNI, which has provided nearly \$21 billion in support since 2000 through numerous federal agencies.¹⁷³ There are also over twenty nanotechnology initiatives run by U.S. state and local governments.¹⁷⁴

Calculating the magnitude of all sources of direct state support for nanotechnology is difficult, but at the national level, 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), each with about \$2.1 billion in spending.¹⁷⁵ Within Europe, the largest funders were Germany, France, the Netherlands, and the United Kingdom.¹⁷⁶ Next were Japan at \$1.3 billion and Russia at \$974 million.¹⁷⁷ The breakdown of global government spending in 2012 is illustrated in Figure 2.

6661, 110th Cong. (2008); Nanotechnology Innovation and Prize Competition Act of 2008, S. 3269, 110th Cong. (2008).

171. For example, the Foresight Institute has established a \$250,000 prize for demonstration of a fifty nanometer, eight-bit adder and a one hundred nanometer robot arm. *See Feynman Grand Prize*, THE FORESIGHT INSTITUTE, <http://www.foresight.org/GrandPrize.1.html> [<http://perma.cc/U3TN-AFK8>].

172. WORLD TECH. EVALUATION CTR., *supra* note 19, at ix.

173. *See* SUBCOMMITTEE ON NANOSCALE SCI., ENG'G, & TECH., OFFICE OF SCI. & TECH. POLICY, *supra* note 16, at 7; WORLD TECH. EVALUATION CTR., *supra* note 19, at 4; *see also* 21st Century Nanotechnology Research and Development Act of 2003 § 7, 15 U.S.C. §§ 7501, 7505 (2003) (authorizing nanotechnology-related expenditures).

174. *See, e.g.*, NAT'L NANOTECHNOLOGY INITIATIVE, REGIONAL, STATE, AND LOCAL INITIATIVES IN NANOTECHNOLOGY 2–3 (2013), http://www.nano.gov/sites/default/files/pub_resource/nni_rsl_2012_rpt_0.pdf [<http://perma.cc/B6YX-YTWP>]; NAT'L RESEARCH COUNCIL, *supra* note 91, at 93 (describing New York's support for the College of Nanoscale Science and Engineering at the University of Albany); Nat'l Nanotechnology Initiative, *Resources at the Regional, State, and Local Level*, NANO.GOV (Jan. 15, 2015), <http://www.nano.gov/initiatives/commercial/state-local> [<http://perma.cc/R959-UEFN>].

175. NANOTECHNOLOGY UPDATE, *supra* note 100, at 3.

176. *Id.* at 4 fig.1.

177. *Id.* The next largest spenders were Canada, Taiwan, Australia, India, Singapore, Brazil, and Israel. *Id.* Total estimated government expenditures by country between 2000 and 2010 were approximately \$11 billion by the United States, \$10 billion by the European Union (from both the European Commission and national governments), \$8 billion by Japan, and \$13 billion by other countries. *See* WORLD TECH. EVALUATION CTR., *supra* note 19, at 17 tbl.5.



Figure 2: Direct Government Nanotechnology Spending
(as share of \$7.9B total in 2012)

Of course, quantifying the direct dollars spent only provides a rough measure of each country's contribution to nanotechnology innovation for at least two reasons. First, as noted above, these figures only include direct transfers from the government. The size of other government-facilitated transfers, including through the IP and R&D tax incentive systems, are more difficult to measure but no less important to innovation policy. Second, even when looking purely at direct transfers, it is critical to consider who gets the money, and under what conditions. 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 energy consumption of seawater desalination to below 1.5 kWh/m³" or the development of solid-state refrigeration systems with energy performance that meets certain metrics.¹⁷⁸ Few legal scholars have turned their attention to the details of direct government R&D spending in the way that they have

178. 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), http://www.whitehouse.gov/sites/default/files/microsites/ostp/PCAST/pcast_fifth_nni_review_oct2014_final.pdf [<https://perma.cc/Q4FM-FECT>].

studied the details of different IP systems, and this area is ripe for further work.

B. Nanotechnology R&D Actors

The nanotechnology innovation ecosystem is comprised of diverse actors, including government laboratories, universities and other nonprofit research institutions, large businesses, and small startups. There is also an array of venture capitalists and other intermediaries that has 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, such as patents, rather than ex ante mechanisms, such as 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.¹⁷⁹

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, they also conduct 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.¹⁸⁰ Brazil has created sixteen science and technology institutes working on nanotechnology, which employ about 2500 researchers.¹⁸¹ The International Iberian Nanotechnology Laboratory in Portugal employs about two hundred scientists.¹⁸²

Private universities and other nonprofit research institutes are also major players in the nanotechnology innovation ecosystem, largely operating off of government grants. Because most 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.¹⁸³ The institutions with the largest

179. See Hemel & Ouellette, *supra* note 93, at 357–58.

180. See Richard P. Appelbaum et al., *Developmental State and Innovation: Nanotechnology in 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).

181. OECD, note 17, at 20.

182. *Id.* at 59.

183. Publications are of course only one measure of a university's impact. Universities also play a key role in developing nanotechnology human capital. Within the United States, the universities that awarded the largest number of nanoscience Ph.D. degrees between 1999

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.

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 2012,¹⁸⁴ though some portion of this spending 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 2012.¹⁸⁵ That corporate spending now exceeds government spending suggests that some nanotechnology sectors are now commercially viable, though continued government support may still be critical to the survival of those sectors. The countries with the largest corporate spenders were the United States, Japan, and Germany, whose companies spent a combined \$7 billion in 2012.¹⁸⁶

and 2009 were MIT, the University of California Berkeley, Northwestern University, the Georgia Institute of Technology, The University of Texas at Austin, the University of Illinois at Urbana-Champaign, the University of Michigan, Stanford University, the University of Minnesota, and Cornell University. James P. Walsh & Claron Ridge, *Knowledge Production and Nanotechnology: Characterizing American Dissertation Research, 1999–2009*, 34 *TECH. IN SOC'Y* 127, 131 tbl.2 (2012).

184. NANOTECHNOLOGY UPDATE, *supra* note 100, at 5.

185. *Id.* at 3.

186. *Id.* at 5.

Table 2: Top Countries and Institutions by Number of Nanotechnology Publications Indexed in Web of Science 1991–2012¹⁸⁷

Rank	Top Countries		Top Institutions	
	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)	8105
4	Germany	50,891	Univ. Tokyo	6932
5	France	44,503	Osaka Univ.	6613
6	South Korea	41,907	Tohoku Univ.	6266
7	England	34,246	U.C. Berkeley	5936
8	India	22,285	CSIC (Spain)	5585
9	Italy	21,474	Univ. Illinois	5580
10	Russia	21,182	MIT	5567
11	Spain	21,054	Nat'l Univ. Singapore	5535
12	Canada	20,960	Univ. Sci. & Tech. China	5527
13	Taiwan	18,449	Peking Univ.	5294
14	Australia	14,728	Indian Inst. Tech.	5123
15	Switzerland	13,664	Univ. Cambridge	5040
16	Netherlands	12,266	Nanjing Univ.	5035
17	Singapore	10,147	Zhejiang Univ.	4836
18	Poland	7953	Seoul Nat'l Univ.	4831
19	Brazil	7097	CNR (Italy)	4679
20	Sweden	6624	Kyoto Univ.	4540

187. Hsinchun Chen et al., *supra* note 62, at 8 tbl.5, 9 tbl.6.

Corporate spenders are numerous and diverse. Some of the earliest nanotechnology companies emerged around 1990, including firms that are still thriving today. Nanophase Technologies, which began in 1989, produces nanomaterials for products including sunscreen, medical diagnostics, and energy.¹⁸⁸ Zyvex Corporation, which began in 1997, provides tools for manipulating and characterizing nanoscale systems for companies in the aerospace, semiconductor, and medical industries.¹⁸⁹ Nano-Tex, which began in 1998, specializes in nanotechnology-based textile enhancements.¹⁹⁰ The corporate nanotechnology landscape has since exploded: from 1990 to 2008, about 17,600 companies worldwide (including 5440 in the United States) published about 52,100 articles and applied for about 45,050 patents related to nanotechnology.¹⁹¹ IBM was the top holder of U.S. nanotechnology patents in both 2004 and 2010.¹⁹² However, 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%.¹⁹³

In 2007, Lux Research created a detailed investment report with profiles of 121 representative companies active in nanotechnology, which provides one window into the IP and legal landscape affecting these companies.¹⁹⁴ For example, the startup SDCmaterials, which creates new nanotechnology catalysts, owned forty patents in 2007 in an area with “a high density of patents and significant overlap.”¹⁹⁵ The small corporation Nanophase, which focuses on creating nanoparticles for further industrial use, also works in a crowded IP space, though Lux Research opined that Nanophase’s IP on its coating technology “stands out.”¹⁹⁶ The world’s largest chemical company, BASF, was operating in a “relatively unencumbered” IP space and had committed to investing €180 million in nanotech R&D from 2006 to 2008, including at a dedicated research center in Singapore and through a col-

188. See *Nanophase Technologies Corp.*, BLOOMBERG BUS., <http://www.bloomberg.com/research/stocks/snapshot/snapshot.asp?ticker=NANX> [<http://perma.cc/K2NV-B6YB>].

189. See *Company Overview of Zyvex Corporation*, BLOOMBERG BUS., <http://www.bloomberg.com/research/stocks/private/snapshot.asp?privcapid=2727765> [<http://perma.cc/9UWH-R8LN>].

190. See *Company Overview of Nano-Tex, Inc.*, BLOOMBERG BUS., <http://www.bloomberg.com/research/stocks/private/snapshot.asp?privcapId=4148462> [<http://perma.cc/99JU-VQDB>].

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

192. WORLD TECH. EVALUATION CTR., *supra* note 19, at 598 tbl.5.

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

194. See generally 2 LUX RESEARCH INC., *supra* note 150 (summarizing factors such as each company’s market, revenue, VC funding, corporate relationships, and IP landscape).

195. *Id.* at 211.

196. *Id.* at 151.

laboration with the University of Strasbourg.¹⁹⁷ The Lux Research report makes clear that corporations are using nanotechnology to support a variety of business models, and that most of these firms are using the IP system to help secure their market positions.

Another view into corporate nanotechnology investment is provided by the OECD's 2012 symposium on assessing the economic value of nanotechnology. Large corporations, such as Lockheed Martin and Michelin, reported nanomaterials research that has led to substantial cost savings.¹⁹⁸ Smaller companies, such as Zyvex Technologies, stated that it often takes ten years to bring nanomaterials to market and emphasized the importance of governments and larger companies in supplying capital to bridge this period before profitability.¹⁹⁹ The nanomedicine company CytImmune Sciences described its process of seeking approval for a nanotechnology-based chemotherapy drug, which involves the same regulatory hurdles as traditional pharmaceuticals.²⁰⁰ QD Vision, an MIT spinoff that produces quantum dots, provides another example of the role of universities in generating early-stage nanotechnologies.²⁰¹

In sum, the nanotechnology innovation ecosystem includes actors from every sector of the broader innovation ecosystem: governments, national laboratories, public and private universities, nonprofits, and for-profit corporations of all sizes. This Article has already examined the various ways that the state supports each of these actors. The next Section will turn to how these actors interact with one another.

C. Knowledge Flows and Tech Transfers in the Nanotechnology Web

The clearest quantitative metrics for measuring knowledge flows and technology transfers 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 those activities cannot be overstated."²⁰² The report highlights the role of professional societies, such as the American Physical Society and the Institute of Electrical and Electronics Engineers, in facilitating these interactions through their conferences.²⁰³

197. *Id.* at 33.

198. OECD, *supra* note 17, at 53–54.

199. *Id.* at 54.

200. *Id.* at 56.

201. *Id.* at 61.

202. NAT'L RESEARCH COUNCIL, *supra* note 91, at 95.

203. *Id.* at 36.

New technologies sometimes follow an orderly progression from academic research to corporate development to a marketed product (though nonlinear paths are also common).²⁰⁴ Venture capital (“VC”) investment, the traditional bridge between academia and industry, was only about \$580 million globally for nanotechnology in 2012.²⁰⁵ This figure is merely three percent of the overall funding of \$7.9 billion from governments plus \$10 billion from corporations.²⁰⁶ Governments and established, cash-rich firms clearly play a more critical role in facilitating nanotechnology development than VC,²⁰⁷ perhaps because the time period to commercialization in nanotechnology remains longer than in other fields,²⁰⁸ or perhaps because governments and large companies are better positioned to manage the infrastructure needed for nanotechnology research.

These infrastructure investments are a key mechanism by which governments facilitate technology transfer. 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 Part II.A.1). The U.S. National Science Foundation funded fourteen facilities at U.S. universities that composed the National Nanotechnology Infrastructure Network.²⁰⁹ 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.²¹⁰ Governments and large corporations may be best suited to create research tools that can be used by a variety of small firms and other actors.

Another tool for facilitating technology transfers from academia to industry is direct spending targeted toward this goal. 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 provides grants to support public/private partnerships.²¹¹ These programs

204. PRESIDENT’S COUNCIL OF ADVISORS ON SCI. & TECH., *supra* note 178, at 42, 44.

205. NANOTECHNOLOGY UPDATE, *supra* note 100, at 6.

206. *Id.* at 3, 5–6.

207. See Tom Crawley et al., Organization for Economic Co-operation and Development, Finance and Investor Models in Nanotechnology 8–10 (Mar. 16, 2012) (unpublished paper prepared for symposium), https://www.nano.gov/sites/default/files/dsti_stp_nano201215.pdf [<https://perma.cc/UHF6-A58F>].

208. Recall that Zyvek’s remarks at the OECD symposium emphasized the importance of governments and large firms in financing startups before profitability. See *supra* note 199 and accompanying text.

209. About Us, NAT’L NANOTECHNOLOGY INFRASTRUCTURE NETWORK, <http://www.nnin.org/about-us> [<http://perma.cc/44D7-W88X>].

210. *Id.*

211. *Frequently Asked Questions*, SBIR/STTR, <http://www.sbir.gov/faq/general> [<https://perma.cc/2CFN-4L86>]. These are not nanotechnology-specific programs, but The National Academies report noted that “nanotechnologies are not unusual in the challenges

awarded \$110 million in nanotechnology grants across agencies in 2012.²¹² Other countries have also used direct support to help launch nanotechnology firms within their borders; 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.²¹³ China's Local Development and Reform Commission provides direct funding for commercialization projects, typically fifteen percent of the total funding needed to set up a company.²¹⁴ This direct funding helps mitigate the risk of entering nanotechnology markets, making entry commercially feasible.

Large companies have been active in helping commercialize nanotechnology products by funding academic research and collaborating with smaller firms.²¹⁵ Specifically, one study explained that "[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."²¹⁶

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 not very 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.²¹⁷ Many lower-income countries view embracing nanotechnology as necessary for long-term economic growth, and some scholars have argued that IP rights and trade barriers are limiting the development of nanotechnology R&D capacity in

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 91, at 13. There are also many U.S. technology transfer programs at the state and regional level. *Id.* at 101.

212. PRESIDENT'S COUNCIL OF ADVISORS ON SCI. & TECH., *supra* note 178, at 42.

213. See OECD, *supra* note 17, at 30.

214. See Appelbaum et al., *supra* note 180, 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, 461 (2009).

215. See, e.g., OECD, *supra* note 17, 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").

216. Corine Genet et al., *Which Model of Technology Transfer for Nanotechnology? A Comparison with Biotech and Microelectronics*, 32 TECHNOVATION 205, 207 (2011).

217. DONALD MACLURCAN, NANOTECHNOLOGY AND GLOBAL EQUALITY 135 (2012).

low-income countries.²¹⁸ Nanotechnology applications of particular interest to developing countries include energy storage, agricultural productivity enhancements, water treatment, and health technologies.²¹⁹

As previously noted, over sixty countries are engaged with nanotechnology R&D on a national level, and a diverse set of countries has hosted and participated in nanotechnology conferences.²²⁰ Some diffusion occurs through formal collaboration agreements, such as the International Center for Nanotechnology and Advanced Materials consortium involving U.S. and Mexican universities.²²¹ Nanotechnology also diffuses through skilled migration. Nanoscientists within the United States are overwhelmingly foreign born, and countries such as China and India have pursued “reverse brain drain” policies to spur the return migration of their nationals.²²² 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.²²³

V. THE ROLE OF THE STATE IN DRIVING INNOVATION

Thus far, this Article has been primarily descriptive, with the goal of capturing the complexity of the nanotechnology innovation ecosystem — its promise and economic impact, the variety of players in this space, and the diverse mechanisms through which innovation occurs. It has examined nanotechnology innovation from a variety of perspectives to help provide a more complete picture. But lest the reader feel like the proverbial blind man trying to describe the elephant, it is worth reflecting briefly on what this information says about different innovation policymaking mechanisms.

Most importantly, it seems clear that IP has been essential in the history of nanotechnology, but also that IP has not been the only important innovation catalyst. In addition to heavy use of the patent system by all actors, significant recurring themes have been (1) the role

218. *Id.* at 137, 147.

219. *Id.* at 154.

220. *Id.* at 197–201.

221. 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, 259 (2009) (documenting that Latin American countries differ vastly from one another in the ratio of within-country, regional, and international collaboration agreements they pursue).

222. James P. Walsh, *The Impact of Foreign-Born Scientists and Engineers on American Nanoscience Research*, 42 SCI. & PUB. POL’Y 107, 112–13, 116–17 (2015).

223. Can Huang & Yilin Wu, *State-Led Technological Development: A Case of China’s Nanotechnology Development*, 40 WORLD DEV. 970, 975–78 (2012).

of universities in supplying both basic research and human capital to the private sector; and (2) the role of the state and large firms in bridging the gap between basic research and commercialization by supplying both capital and expensive infrastructure.

So what does nanotechnology innovation policy reveal about broader debates on innovation policy? As discussed in Part I, one strand of scholarship utilizes case studies of areas in which innovation has flourished without IP (“IP’s negative space”) to question whether IP is necessary more broadly. This Article sounds a note of caution about extrapolating from such studies. Nanotechnology innovation appears to be thriving alongside intensive use of IP systems. While this does not necessarily mean that IP is indispensable to nanotechnology innovation, it does demonstrate that nanotechnology would not have developed in the same way without it. The difficulty of drawing strong conclusions about fundamental issues of IP policy — such as whether we are better off with patents or without — is a persistent source of frustration for scholars, but case studies are not a magic bullet for resolving this uncertainty.²²⁴

Another strand of scholarship presented in Part I focuses on the benefits of private sector over public sector innovation, arguing that “[g]overnments have always been lousy at picking winners” and should stick to providing “a level playing field for enterprises of all kinds.”²²⁵ It asserts that providing a relatively level playing field through the patent system is an important role for the state. As discussed above, however, the patent system itself is not necessarily neutral because government actors have many policy levers to adjust it for new technologies, including limitations on patentable subject matter and disclosure requirements.

Furthermore, nanotechnology serves as a useful counterpoint to the common narrative of an independent private sector that will produce breakthrough innovations as long as the government leaves it alone. As this Article has explained, governments have not simply relied on technology neutral innovation policies such as patents and general R&D tax credits for nanotechnology.²²⁶ A passive strategy would not have been very successful: As discussed in Part IV, venture capitalists have played a relatively minor role in the development of nanotechnology, making private sector financing difficult. This is like-

224. See generally Ouellette, *supra* note 4, at 75–84 (discussing how a variety of approaches, including case studies, have been unable to answer these fundamental empirical questions).

225. *The Third Industrial Revolution*, THE ECONOMIST (Apr. 21, 2012), <http://www.economist.com/node/21553017> [<http://perma.cc/GJ6K-6C6X>]; see also *supra* notes 12–13 and accompanying text (noting this conventional wisdom).

226. For a discussion of the difference between technology neutral policies in which the reward for innovators is determined by the market, and technology-specific policies in which the government targets particular technologies for grants and prizes, see *supra* note 163 and accompanying text.

ly why over sixty countries have created national nanotechnology R&D programs that actively direct and support private sector nanotechnology research.

Governments have also helped finance nanotechnology research through a variety of other mechanisms. Perhaps most significantly, governments have directly supplied critical infrastructure, such as the National Nanotechnology Infrastructure Network, for nanotechnology innovation. For capital-intensive technologies, these investments are essential to lowering barriers to entry.²²⁷

The state plays a critical role not only in providing financial capital to firms, but also in developing their human capital. A number of commentators have recognized that the state can affect innovation and growth through labor and employment laws, such as by limiting firms' ability to constrain workers through noncompetition agreements.²²⁸ The state also directly invests in human capital development through education. One could of course trace this investment back to early childhood education, but the most direct development of skills needed for nanotechnology research occurs in universities. The science and engineering professors who teach future nanotechnology researchers largely finance their research through government funding.²²⁹ The majority of this funding supports the students and postdoctoral workers who run their labs.²³⁰

When discussing private sector research, it is thus important to remember that most industry researchers received significant training in academic settings, often with substantial government support. This is not a recent phenomenon. As described in Part II.A.1, both the TEM and the SEM were developed by researchers who did foundational work on these microscopes as part of their Ph.D. studies and subsequently moved to private firms that created commercially viable versions. Similarly, the STEM was developed after an academic reached out to a firm and worked with it to modify one of its existing

227. See generally BRETT M. FRISCHMANN, *INFRASTRUCTURE: THE SOCIAL VALUE OF SHARED RESOURCES* (2012).

228. See generally ORLY LOBEL, *TALENT WANTS TO BE FREE* (2013); ANNALEE SAXENIAN, *REGIONAL ADVANTAGE: CULTURE AND COMPETITION IN SILICON VALLEY AND ROUTE 128* (1996); Ronald J. Gilson, *The Legal Infrastructure of High Technology Industrial Districts: Silicon Valley, Route 128, and Covenants Not To Compete*, 74 N.Y.U. L. REV. 575 (1999).

229. See NAT'L SCI. BD., *SCIENCE & ENGINEERING INDICATORS 5-5* (2014), <http://www.nsf.gov/statistics/seind14/content/etc/nsb1401.pdf> [<http://perma.cc/LH8J-HEKW>] (reporting that "[t]he federal government provided about 60% of total academic R&D in FY 2012," while private businesses provided "just over 5%").

230. See *id.* at 5-5, 5-21 (reporting that, of \$62 billion spent by academic institutions on science and engineering research in fiscal year 2012, only about \$5 billion was spent on research equipment or repairs and renovations of research space; the remaining \$57 billion was spent on personnel and new construction, with construction primarily funded by institutions other than the government).

products. And an industry researcher developed the AFM while on leave from Stanford.

These examples also illustrate that university trained researchers are important for facilitating knowledge transfers. The legal literature on innovation has primarily focused on the role of patents (as opposed to people) in mediating the transfer of ideas from conception in academic labs to commercialization by firms. In particular, the commercial development of university inventions was the primary goal of the Bayh-Dole Act of 1980, which clarified that recipients of federal grants can patent their new technologies “to promote the utilization of inventions arising from federally supported research.”²³¹ But the literature has mostly overlooked the significant role of human capital in facilitating this process.

VI. CONCLUSION

As this Article has explained, the nanotechnology innovation ecosystem is a microcosm of the general innovation ecosystem. The role of the IP system in nanotechnology innovation seems similar to its role in general, with all of the corresponding costs and benefits. This overview of the nanotechnology innovation ecosystem serves as a useful counterpoint to both the growing number of case studies exploring how innovation flourishes without intellectual property, and the myth of an independent private sector that produces breakthrough innovations without government intervention. Nanotechnology is one field that likely would not have evolved as rapidly without significant government involvement. In addition to creating and managing IP systems, governments have played a very active role in guiding and supporting private sector nanotechnology innovation through direct investments in infrastructure, financial capital, and human capital. The data suggests that VC and other private sector activity would not have compensated for these direct investments had they been distributed elsewhere.

This is not to say that studies of IP’s negative space or critiques of wasteful government spending are not worthwhile. There is value in showing that patents are not always necessary for innovation and that government efforts to pick winners have often backfired, especially if the authors of these studies can explain *why*. Case studies can help refine a theory or generate new hypotheses; however, there are limits to their ability to draw strong conclusions about causation.²³² This

231. 35 U.S.C. § 200 (2012); *see also* Bhaven N. Sampat, *Patenting and US Academic Research in the 20th Century: The World Before and After Bayh-Dole*, 35 RES. POL’Y 772, 772 (2006).

232. *See* Ouellette, *supra* note 4, at 78, 99 (discussing the importance of pinpointing the correct causal mechanism behind observed effects).

study is no exception. Certainly, the lessons from nanotechnology's history must be qualified: A different mix of innovation policies may well have worked better for nanotechnology, and the mix of policies used for nanotechnology may not work well for a different technological field.²³³ The purpose of this Article is simply to provide support for some specific theories about innovation systems, for example, by illustrating that shared infrastructure can be effective in encouraging entry into capital-intensive fields. Just as importantly, it should give innovation policymakers a healthy dose of skepticism about broad claims based on isolated case studies. The mix of innovation policies presented here appears to have worked well for nanotechnology, and it is promising that none of the many actors involved in nanotechnology innovation are complaining that the system is broken.²³⁴

In exploring ways that innovation occurs without reliance on IP, researchers should not lose sight of the fact that innovation also frequently occurs *with* heavy reliance on IP. Policymakers should thus be wary of relying on conclusions from disparate fields when making significant innovation policy changes. This does not mean, however, that understanding the causal impact of innovation laws is impossible. As explained previously, making empirical progress in innovation policy is difficult in large part due to the lack of meaningful policy diversity.²³⁵ The challenge of drawing robust conclusions from isolated case studies should demonstrate to policymakers the importance of introducing greater variation in innovation laws, either through randomized policy experiments or through experimentalist interventions.²³⁶ It's not too late for nanotechnology: The billions of government dollars that are still directed toward this field each year could be spent in ways far more useful for evidence-based learning.

233. Cf. Hemel & Ouellette, *supra* note 93, at 375–82 (explaining that the optimal mix of innovation policies will vary with different technologies and contexts).

234. In contrast, many software researchers feel that the patent system does not work for software innovation. See, e.g., Eric Goldman, *Two Challenges to Fixing Software Patents (Part 2 of 3)*, FORBES (Dec. 11, 2012), <http://www.forbes.com/sites/ericgoldman/2012/12/11/two-challenges-to-fixing-software-patents/> [<http://perma.cc/V8KF-MYJE>].

235. Ouellette, *supra* note 4.

236. See *id.* (contrasting these approaches and giving specific examples of how they should be applied to different aspects of innovation policy).