From Lab to iPod

A Story of Discovery and Commercialization in the Post–Cold War Era

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In 1988, two European scientists independently discovered that tiny changes in magnetism can produce unexpectedly strong electrical signals. Within a decade, their seemingly esoteric observation—a phenomenon physicists dubbed "giant magnetoresistance," or GMR—revolutionized the electronics industry as it facilitated the ability of computer disk drives to store ever-increasing amounts of data. When the Royal Swedish Academy of Sciences awarded the 2007 Nobel Prize in Physics to Peter Grünberg and Albert Fert, journalists and scientists immediately associated their laboratory research with today's ubiquitous electronic gadgets. "You would not have an iPod without this effect," claimed an academy member when the prize was announced, referring to Apple's bestselling music player.[1] Optimistic experts in

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1. Quote by Borje Johansson, in Dennis Overbye, "Advance in Data Storage Led to

the electronics industry predicted that research like Fert and Grünberg's might lead to "new approaches to emerging research [in] memory, logic, and nano-architecture" and, consequently, new products.[2]

Media claims surrounding the 2007 Nobel announcement reflected the nature of modern technoscientific knowledge production as reporters conflated the observation of a new physics phenomenon with the engineering of new electronics devices. The discovery also signaled the emergence of new research communities.[3] Fert and Grünberg's work, newspapers reported, had catalyzed a growing field of interdisciplinary research called "spintronics." Following the 1988 discovery, groups of experimental physicists, theoreticians, and electrical engineers explored the science of electron spin and how it might be used to fabricate new devices.[4]

The Royal Swedish Academy's announcement noted that the devices following from Fert and Grünberg's discovery were among "the first real applications of the promising field of nanotechnology."[5] Scientists could claim that the initial discovery of GMR required laboratory-fabricated samples made of extraordinarily fine layers of materials less than ten billionths of a meter thick. The subsequent work of spintronics researchers involved equally precise manipulations of matter to construct and characterize novel structures and devices. In the United States, enthusiastic scientists, engineers, and policy makers interpreted the commercialization of Fert and Grünberg's European-based discovery as a sign that their country's investment of time and funding into nanotechnology was both sensi-

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iPod and Now Nobel," *New York Times*, 10 October 2007. The first iPods, introduced in 2001, used a 1.8-inch hard drive made by Toshiba to store up to ten gigabytes of music files. The most recent versions store sixteen times as much data.

2. International Roadmap Committee, "Emerging Research Devices" (Austin, Tex., 2005), 1.

3. Headlines for the 2007 Nobel Prize attest to this; for example: "Physics of Hard Drives Wins Nobel" (*New York Times*) and "Effect That Revolutionized Hard Drives Nets a Nobel" (*Science*).

4. For decades, the electronics industry was based on manipulating the charge of electrons moving through circuits and transistors; however, manipulating an electron's spin is faster and might require less energy than using its inherent charge. As subatomic particles, electrons do not actually spin; instead, they can have two weak magnetic-energy states, which can be thought of as "spin up" and "spin down." Spin is a quantum number assigned to the electron because of this intrinsic rotation. In conventional electronic devices, these states fluctuate randomly. Moreover, different spin states of electrons have different energies and, consequently, a weak magnetic moment. This makes them behave like tiny bar magnets, enabling researchers to control them with electric and magnetic fields. Because spintronics combines electrical and magnetic phenomena, it was initially (and still is occasionally) referred to with the less-catchy name of "magnetoelectronics."

5. From the 9 October 2007 Nobel Prize announcement. This, along with the scientific background, interviews with the prizewinners, and their acceptance speeches, are archived at http://nobelprize.org/nobel_prizes/physics/laureates/2007/ (hereafter abbreviated as "NP2007," accessed 30 April 2008).

ble and prescient.[6] The resulting flood of research monies transformed nanotechnology into one of the most robustly funded, aggressively pursued, and widely promoted fields in modern science and engineering.[7]

This essay considers how spintronics emerged from Fert and Grünberg's discovery to become, in the 1990s, a new subfield that blended novel solid-state physics and device engineering with well-established areas of research such as magnetics and materials science. This history highlights the significant role that materials and instrumental capabilities have played in nanotechnology-related research, and the concomitant need for scholars studying modern engineering science to take this into account.[8]

Researching this discovery and the work that came after it presents a historiographical challenge. The story is quite recent, making correspondence and laboratory notebooks relatively inaccessible. Instead, the evidentiary base consists of hundreds of technical papers, along with extensive coverage (typically in business-related stories) in newspapers and mainstream science publications like *Nature*. At the same time, oral history provides a potentially valuable resource, so long as one approaches such interviews with an especially critical eye, as the principal actors are still publishing research and seeking funding.[9]

Nevertheless, these diverse sources enable us to see how spintronics grew from an early focus on metal-based systems to encompass a much broader research program that included semiconductors—the basic mate-

6. See, for example, Mihail C. Roco, Stan Williams, and Paul Alivisatos, eds., *Nanotechnology Research Directions: IWGN Workshop Report* (Baltimore, 1999). One section (78) notes that GMR was "the most recent success story" in the emerging area of nanotechnology, which had transformed a market worth well over $30 billion annually.

7. W. Patrick McCray, "Will Small Be Beautiful? Making Policies for Our Nanotech Future," *History and Technology* 21 (2005): 177–203. Based on government-funding levels, nanotechnology represents the biggest single civilian investment in technology since the Apollo program. According to the National Nanotechnology Initiative, the United States' major effort in this area, nanotechnology is "the understanding and control of matter at dimensions of roughly 1-to-100 nanometers, where unique phenomena enable novel applications" (from http://www.nano.gov, last accessed 30 April 2008). A nanometer is one-billionth of a meter; a page from this journal is about 100,000 nanometers thick.

8. Christophe Lécuyer and David C. Brock note that *materiality* is central for understanding the history of microelectronics and argue for the importance of materials as an analytical category to complement device-oriented historiography. A similar case can be made for spintronics. See Lécuyer and Brock, "The Materiality of Microelectronics," *History and Technology* 22 (2006): 301–25. Similarly, a recent article on probe microscopy highlights the central importance of instrumentation in modern nanoscale research; see Cyrus C. M. Mody, "Corporations, Universities, and Instrumental Communities: Commercializing Probe Microscopy, 1981–1996," *Technology and Culture* 47 (2006): 56–80.

9. One is reminded of Otto Neugebauer's comment: "The common belief that we gain 'historical perspective' with increasing distance seems to me to utterly misrepresent the actual situation. What we obtain is merely confidence in generalizations which we could never dare make if we had access to the real wealth of contemporary evidence" (from *The Exact Sciences in Antiquity* [Providence, R.I., 1957], viii).

rials underlying the entire modern electronics industry. Engineers directed much of their research and commercial development toward devices for data storage, such as computer hard drives. This essay, therefore, complements the existing historiography of the electronics industry, which has emphasized other technologies such as semiconductors, integrated circuits, computer hardware, or the development of the internet itself.[10]

For years, technological pundits have predicted the imminent demise of "Moore's Law." Intel founder Gordon Moore made this observation in 1965, noting that the density of transistors on integrated circuits was (and would continue) doubling at regular intervals.[11] Although a self-fulfilling and socially constructed "prophecy," the expectations of Moore's Law have shaped technology developments and expectations in the electronics industry for more than forty years.[12] At some point over the technological horizon, however, industry experts insist that basic engineering factors will constrain additional miniaturization.[13] Researchers interested in spintronics hope that their exploitation of electron spin will toll the final bell on silicon-and-charge-based devices, just as the transistor helped usher out the era of vacuum tubes in the 1950s. Spintronics' history, therefore, offers a perspective on how the contemporary electronics and semiconductor industries grapple with technological uncertainty.[14] Research on spintronics and other

10. Recent excellent book-length examples of this scholarship include: Ross Knox Bassett, *To the Digital Age: Research Labs, Start-Up Companies, and the Rise of MOS Technology* (Baltimore, 2002); Paul Ceruzzi, *A History of Modern Computing* (Cambridge, Mass., 2003); John Markoff, *What the Dormouse Said: How the Sixties Counterculture Shaped the Personal Computer Industry* (New York, 2005); and Christophe Lécuyer, *Making Silicon Valley: Innovation and the Growth of High Tech, 1930–1970* (Cambridge, Mass., 2006). A valuable overview, although now somewhat dated, is Roy Rosenzweig, "Wizards, Bureaucrats, Warriors, and Hackers: Writing the History of the Internet," *American Historical Review* 108 (1998): 1530–52.

11. Gordon E. Moore, "Cramming More Components onto Integrated Circuits," *Electronics* 38, no. 8 (1965): 114–17; and David C. Brock, ed., *Understanding Moore's Law: Four Decades of Innovation* (Philadelphia, 2006).

12. Paul E. Ceruzzi, "Moore's Law and Technological Determinism: Reflections on the History of Technology," *Technology and Culture* 46 (2005): 584–93.

13. Conventional transistors function as microscopic on/off switches. They have a source (where electrons originate), a drain (where they exit), and a gate that controls the flow in a way that connects the source and the drain. At some point, basic engineering factors such as heat dissipation and electron tunneling will limit additional miniaturization. See Paolo A. Gargini, "Silicon Nanoelectronics and Beyond," *Journal of Nanoparticle Research* 6 (2003): 11–26.

14. One way the semiconductor industry does this is through the use of technology roadmaps. These have received considerable attention from economists and industry analysts, but less so from historians. For a thorough review of the topic, which combines economics and history, see Robert R. Schaller, "Technological Innovation in the Semiconductor Industry: A Case Study of the International Technology Roadmap for Semiconductors (ITRS)" (Ph.D. diss., George Mason University, 2004). Ann Johnson's "Top-Down Science: The Role of Roadmaps in the Development of Nanotechnology," presented at the Joint Wharton–Chemical Heritage Foundation Symposium on Social

areas of "exotic physics" provides a way for industry executives to hedge their bets until they secure a vantage point with a clearer view over the technological horizon.[15] As such, spintronics compares with other exploratory technologies, such as molecular electronics and high-temperature superconductivity, that firms such as IBM and Bell Labs invested heavily in.[16]

Funding from military agencies interested in potential applications facilitated the emergence of a spintronics research community. The Defense Advanced Research Projects Agency (DARPA) was one of the technology's first champions. Founded in the wake of Sputnik, DARPA had a reputation among scientists as lean, agile, and eager to direct considerable resources to high-risk, high-payoff technologies. During the 1990s, DARPA invested millions of dollars into university-based spintronics research, funding both applications-oriented and fundamental studies. The growth of spintronics as both a discrete field of physics and a research community provides insight into the role of military sponsorship in fostering knowledge production.[17] While scholars have largely focused their attention on the cold war era, the story of spintronics propels us forward into the post–cold war and, eventually, the post-9/11 era.

Studies of Nanotechnology on 7 June 2007, describes how technology roadmaps rationalize the corporate R&D process by suggesting realistic ways to achieve goals (copy in author's possession). Technology roadmaps reflect, she argues, an ideology based on progress consistent with a modernist, rationalist approach to policy making—an idea that draws on James Scott's *Seeing Like a State: How Certain Schemes to Improve the Human Condition Have Failed* (New Haven, Conn., 1999).

15. Toni Feder, "Industry and Academia Join Hands in Search for Post-CMOS Logic," *Physics Today*, May 2006, 22–23.

16. Hyungsub Choi and Cyrus C. M. Mody, "Molecular Electronics in the Long Durée," *Social Studies of Science*, forthcoming; Helga Nowotny and Ulrike Felt, *After the Breakthrough: The Emergence of High Temperature Superconductivity as a Research Field* (New York, 1997).

17. The literature on this topic is considerable. Especially relevant for this essay are: Thomas J. Misa, "Military Needs, Commercial Realities, and the Development of the Transistor, 1948–1958," in *Military Enterprise and Technological Change: Perspectives on the American Experience*, ed. Merritt Roe Smith (Cambridge, Mass., 1985), 253–87; Paul Forman, "Behind Quantum Electronics: National Security as Basis for Physical Research in the United States, 1940–1960," *Historical Studies in the Physical and Biological Sciences* 18 (1987): 149–229; and Stuart Leslie, *The Cold War and American Science: The Military-Industrial Complex at M.I.T and Stanford* (New York, 1993). Not all historians agreed with Forman's "distortionist" view, including, most notably, Daniel J. Kevles (in "Cold War and Hot Physics: Science, Security, and the American State," *Historical Studies in the Physical and Biological Sciences* 20 [1990]: 239–64), who objected to the idea that scientists were seduced from some "true path" by military funding and argued that "physics is what physicists do." While Forman's thesis sparked considerable debate and historical inquiry into the question of how the cold war might have affected scientists' research agendas—what one might call "cold war determinism"—some tenets of it have been challenged more recently; see, for example, Joan Lisa Bromberg, "Device Physics vis-à-vis Fundamental Physics in Cold War America: The Case of Quantum Optics," *Isis* 97 (2006): 237–59.

At the same time, the success of spintronics and the broader needs of the electronics industry helped generate strong political support for national nanotechnology programs in the United States, Europe, and Asia. While major results from the so-called nano-revolution have yet to appear, the fact that as much as $10 billion annually is spent worldwide on research related to nanotechnologies should prompt historians of technology to raise questions about the circumstances, context, and rationale of the nano-enterprise.[18] While healthy support from the National Science Foundation has helped spawn a burgeoning research community to address societal and ethical questions about nanotechnology, historians have generally been less engaged in the topic. This article contributes to our understanding of what is inside the "black box" of nanotechnology and how it got there. Fert and Grünberg discovered GMR in the tradition of small-scale, basic physics research. Businesses then swiftly patented and integrated it into scores of products worth billions of dollars in annual sales.[19] Examining the circumstances underlying this Nobel Prize–winning research, exploring its subsequent commercialization, and considering the interdisciplinary community that subsequently formed provide a lens to view the broader context of basic research and engineering application in the era of "post-academic" science in which research is often driven by utility and practical problems.[20] In the story of spintronics, we can discern connections between contemporary scientific research and commercial engineering applications, while gaining some insight into recent historiographical discussions that have begun to reexamine the boundaries and shifting relations between science and technology.[21]

"It's daunting physics . . ."[22]

Since the nineteenth century, scientists and engineers knew that the resistance of an electrical conductor like iron changed when placed in a magnetic field. The essence of this "magnetoresistance" effect, noted in 1857 by the British scientist William Thomson (also known as Lord Kelvin), formed

18. Estimate given by Max Bünger, director of research for Lux Research Inc., in a talk to the American Physical Society (13 November 2006) titled, "The Economics of Matter: Nanotechnology and Scale of Manufacturing," available at http://www.aip.org/ca/2006/program.html (accessed 30 April 2008).

19. One estimate is that over five billion hard drives featuring GMR-related technology have been sold since 1997; Charles Day, "Discoverers of Giant Magnetoresistance Win This Year's Physics Nobel," *Physics Today*, December 2007, 12–14.

20. John Ziman, *Real Science: What It Is and What It Means* (New York, 2000).

21. The most notable example of this scholarship is Paul Forman's erudite and contentious essay—"The Primacy of Science in Modernity, of Technology in Postmodernity, and of Ideology in the History of Technology," *History and Technology* 23 (2007): 1–152—and the debate it has stimulated among historians of technology.

22. From 9 October 2007 interview with Albert Fert; NP2007.

the basis for applications such as early computer memory storage and sensors that could detect magnetic fields. Meanwhile, a theoretical understanding of electron spin dates back to the golden era of quantum mechanics in the 1920s and the work of scientific luminaries like Samuel Goudsmit, Wolfgang Pauli, and Paul Dirac. In 1959, Caltech physicist and future Nobel laureate Richard Feynman, in an after-dinner address to the American Physical Society that many scholars have interpreted as the *ur*-speech for nanotechnology, predicted that future electronics might use an electron's spin as well as its charge. "Atoms on a small scale behave like *nothing* on a large scale, for they satisfy the laws of quantum mechanics," Feynman noted. "We can use, not just circuits, but some system involving the quantized energy levels, or the interactions of quantized spins, etc."[23]

The "etc." Feynman ended his sentence with indicates how abstract scientists' thoughts on this topic were in 1959. The integrated circuit itself was barely a year old. Before any concrete advances could be made utilizing electron spin, scientists needed new tools and techniques. One challenge scientists and engineers faced was an inability to construct novel experimental materials with the desired degree of control and precision. During the 1960s and 1970s, scientists at industrial firms such as Bell Labs and IBM experimented with several techniques that enabled them to fabricate artificial (i.e., not found in nature) materials.[24] Motivated by their desire to construct and study new semiconductor materials, for instance, scientists and engineers developed molecular beam epitaxy (MBE). With MBE, pure sources of material are vaporized in separate ovens. Lab technicians (and, later, computer-controlled shutters) released the atoms or molecules into vacuum chambers, where they diffused as a "beam" to a substrate. By carefully controlling the source materials and the deposition rate, scientists could build new "nanostructures" with precisely controlled chemical compositions one atomic layer at a time. MBE became a key instrumental capability for nanoscale engineering and would prove indispensable to Fert and Grünberg's research.

Although they shared the 2007 Nobel Prize, Albert Fert (b. 1938) and Peter Grünberg (b. 1939) did their research at laboratories in different countries. Despite their different nationalities—Fert is French and Grünberg, German—the two men had similar backgrounds. Both scientists were roughly the same age, born just before the start of World War II, and they earned their degrees in physics within a year of each other.[25] During the

23. Richard P. Feynman, "There's Plenty of Room at the Bottom," *Engineering & Science*, February 1960, 22–36. On the questionable importance of Feynman's talk for the origin of nanotechnology, see Chris Toumey, "Apostolic Succession," *Engineering & Science*, January 2005, 16–23.

24. W. Patrick McCray, "MBE Deserves a Place in the History Books," *Nature Nanotechnology* 2 (2007): 2–4.

25. Biographical information on the two scientists is at NP2007.

1970s and 1980s, Grünberg, working at the Jülich Research Center in western Germany, studied the behavior of exotic semiconducting materials like europium oxide before switching his investigation to metals. Fert, in comparison, worked strictly with magnetic metals as both a theorist and experimentalist at the Laboratoire de Physique des Solides at the University of Paris-Sud.

The behavior of metal multilayers, a field of research dating back to the 1960s, interested both Grünberg and Fert. For years, scientists had studied metal multilayers as they investigated superconductivity phenomena and developed stronger composites. As their research progressed, both physicists faced the question of how to fashion experimental samples from the nanoscale layers of metals. MBE offered a solution to this technical obstacle and, as a result, one could label their research "nanotechnology" years before the word itself fully entered the popular lexicon.

Fert's team fabricated its samples from some thirty alternating layers of iron and chromium, each less than ten nanometers thick.[26] In comparison, Grünberg's group studied iron and chromium tri-layers. Both teams observed unexpectedly large changes in the samples' electrical resistance in response to relatively small magnetic fields, with Fert seeing a stronger effect because his samples had more layers. While the French team coined the term "giant magnetoresistance," Grünberg recognized that the GMR phenomenon could help detect faint magnetic fields and therefore filed for a patent as his group wrote up its results. In mid-1988, both research teams presented their results at a conference in Le Creusot, France, and submitted their studies for publication in *Physical Review*.[27] Now aware of each other's work, the two scientists agreed to share credit for the discovery.[28]

Commercializing GMR

After the French and German teams announced the discovery of GMR and Grünberg applied for patent protection, other researchers realized the phenomenon could serve as the basis for new electronic devices. Consequently, early metals-based spintronics transformed a laboratory curiosity into the basis of real-world applications. The relative swiftness of this dis-

26. A good description of this research is in Day (n. 19 above).

27. For the original papers, see M. N. Baibich et al., "Giant Magnetoresistance of (001)Fe/(001)Cr Magnetic Superlattices," *Physical Review Letters* 61 (1988): 2472–75; and G. Binasch et al., "Enhanced Magnetoresistance in Layered Magnetic Structures with Antiferromagnetic Interlayer Exchanges," *Physical Review B* 39 (1989): 4828–30.

28. In a 2003 press release issued by the Centre National de la Recherche Scientifique, Fert went on the record with this statement of shared discovery: "Grünberg and I agreed from the beginning to consider that our experiments had taken place almost simultaneously and that we thus shared the discovery of GMR." Press release at http://www.cnrs.fr/cw/en/pres/compress/Albert_Fert.htm (accessed 30 April 2008).

covery-to-device path encouraged the electronics industry to consider spintronics as an over-the-horizon technology worth investigating further.

Engineers first applied the GMR phenomenon to devices for detecting slight magnetic fields.[29] Subsequent applications for these GMR-based sensors included niche products such as landmine-detection tools and traffic-control systems.[30] This industrial interest reflected a broader tradition of defense-sponsored research on magnetic materials and sensors that dated to the late 1950s. The U.S. Navy, for instance, had long been interested in using superconducting quantum-interference devices, or SQUIDs, to detect enemy submarines.[31] And superconductivity itself was one of the hottest fields for materials scientists in the late 1980s, especially after the 1986 discovery of high-temperature superconductivity at an IBM lab in Zurich.[32] Many researchers who eventually joined the spintronics community had some superconductivity research on their résumés, an understandable overlap given that both topics concerned magnetic phenomena.[33]

Companies were eager to apply the nascent form of spintronics to broader and more lucrative markets. Following the discovery of GMR, scientists at IBM's Almaden laboratory near San Jose, California, searched for other ways to apply it to commercial products. Unlike IBM's Thomas J. Watson Research Center in Yorktown Heights, New York, which had a long

29. For instance, James M. Daughton helped introduce an early commercial application of GMR and metal-based spintronics. Trained as an electrical engineer, Daughton first worked on magnetic-memory devices at IBM's lab in Yorktown Heights, New York, before starting a company called Nonvolatile Electronics in 1989. See J. Daughton et al., "Magnetic Field Sensors Using GMR Multilayer," *IEEE Transactions on Magnetics* 30 (1994): 4608–10.

30. As reported by the National Institute for Standards and Technology, dated January 1999, in promotion of its Advanced Technology Program: http://www.nist.gov/public_affairs/factsheet/nve2.htm (accessed 30 April 2008).

31. SQUIDs were first developed in 1964 by scientists at Ford Research Labs. Their ability to detect faint magnetic fields meant that they could also be used for applications like mineral prospecting and neurological research. These devices make use of the flow of current across two superconductors separated by a thin insulating layer; the effect was discovered in 1962 by Brian D. Josephson, who shared the 1973 Nobel Prize in Physics for his work. As Cyrus Mody has pointed out in his paper "The Long Arm of Moore's Law" (forthcoming), there was considerable transfer of researchers and knowledge from failed commercial attempts (led by IBM, which invested well over $100 million into the effort) to develop computers based on Josephson junctions. Several of these researchers ended up as key players in the scanning tunneling microscopy and nanofabrication communities. My thanks to Dr. Mody for sharing a draft of his paper with me.

32. For instance, see Ulrike Felt and Helga Nowotny, "Striking Gold in the 1990s: The Discovery of High-Temperature Superconductivity and Its Impact on the Science System," *Science, Technology, and Human Values* 17 (1992): 506–31, as well as their book, *After the Breakthrough* (n. 16 above). Although the levels of government funding were quite different, the hype surrounding high-temperature superconductivity in the late 1980s presaged the flood of interest that accompanied carbon nanotubes, buckyballs, and nanotechnology in general a decade later.

33. More precisely, superconductivity refers to a phenomenon marked by a material's zero electrical resistance and exclusion of magnetic fields at extremely low temperatures.

history of research on semiconductor logic devices, the older Almaden lab had traditionally focused on magnetic information-storage technologies.

One of the IBM researchers who engaged with this new research program was Stuart Parkin. In 1980, Parkin earned his doctorate in physics while working at the Cavendish Laboratory in Cambridge. Two years later, still in his twenties, he joined the Almaden scientific staff, where he initially researched topics such as high-temperature superconductivity. After learning about Fert and Grünberg's research, he began to explore the magnetic properties of multilayer thin films with an eye toward improving the capabilities of his company's hard-disk drives.

In 1991, Parkin and his colleagues filed for a patent for what they called a "spin valve."[34] Exploiting the GMR effect, in its basic form, a spin valve is composed of two magnetic layers separated by a nonmagnetic layer. When the magnetic moment of the layers is aligned, electrons move between them more easily and the sample shows low resistance. If the magnetic layers are not aligned, the spin-dependent movement of electrons is impeded and resistance goes up. In this way, the device acts as a valve, affecting the passage of electrons depending on whether it is "open" or "closed."[35]

Unlike Fert and Grünberg, who built their samples with the more precise but slower molecular beam epitaxy technique, Parkin's group adopted sputter-deposition equipment.[36] The focus of the Almaden group wasn't on basic science per se, but on making devices that could be readily manufactured. Parkin's use of the quicker and cheaper sputtering technique made sense for IBM, a company with extensive experience in fabricating sputter-deposited magnetic-storage media on an industrial scale. As one observer of Parkin's research later recalled, the British scientist and his colleagues "simply engineered the [expletive deleted]" out of the underlying GMR discovery as they made and characterized over 30,000 different multilayer combinations.[37]

34. Research described in B. Dieny et al., "Giant Magnetoresistance in Soft Ferromagnetic Multilayers," *Physical Review B* 43 (1991): 1297–1300. The patent was awarded in October 1992: "Magnetoresistive Sensor Based on the Spin Valve Effect," United States Patent no. 5,159,513 (27 October 1992), assigned to IBM based on an invention by Bernard Dieny, Bruce Gurney, Serhat Metin, Stuart Parkin, and Virgil Speriosu.

35. Whether the magnetic moments of the ferromagnetic layers are aligned depends on the application of an external magnetic field that, in effect, acts as a switch. This background information is from a 1992 interview with Parkin by *Science Watch*: "Magnetic Multilayers May Dispel Data Density Dilemma," available at http://www.sciencewatch.com/interviews/stuart_parkin1.htm (accessed 30 April 2008).

36. This is a form of vapor deposition in which material is eroded from a "target" and then transported and deposited on a substrate. Nominally similar to MBE, sputter techniques allow for faster deposition and require less expensive equipment, with the tradeoff being that the resulting layers have more defects.

37. This research is described in numerous publications, including press materials presented on the IBM website at http://www.research.ibm.com/research/gmr.html (accessed 30 April 2008). The quote is from David D. Awschalom, in April 2006 interviews with W. Patrick McCray.

IBM eventually used the spintronics research of Parkin and his colleagues to redesign and improve a basic element in the company's hard-disk drives. The *Wall Street Journal* revealed the company's innovation with a front-page story in November 1997. Based on the Almaden group's exploitation of GMR, IBM's new drives featured exquisitely sensitive magnetic-read heads.[38] Able to store eight times more data than competitors' equipment while remaining smaller in size, the redesigned read heads set the stage for a subsequent explosion in computer memory that, in turn, helped make it possible for music lovers to store gigabytes of music and other files on iPods and similar handheld gadgets.[39]

IBM licensed its GMR-based technology to other companies and, within a few years, practically every computer hard drive included a read head based on IBM's innovation. Firms like Seagate Technology and, for awhile, IBM reaped tremendous profits.[40] IBM's rapid commercialization of Fert and Grünberg's basic discovery introduced spintronics into a market worth billions of dollars annually. And while these ubiquitous tools were not explicitly marketed as nanotechnology, IBM researchers could boast that, because of their research, "everybody has [a] spintronics device on their desktop."[41]

38. The actual device IBM engineers and scientists developed worked in the following fashion: as the sensor moved above tracks of data on the hard disk, the magnetized domains (which represented the 0s and 1s of binary code) flipped the unpinned layer from parallel to anti-parallel or vice versa. This changed the resistance and thus the current through the sensor as it moved only about ten nanometers above the disk's surface at speeds approaching 80 miles per hour. In this manner, reading from the hard drive took place. The advantage of IBM's read heads came from the fact that more sensitive devices can register smaller magnetized domains on the surface of hard drives, resulting in increased storage density.

39. Raju Narisetti, "IBM Unveils Powerful PC Disk Drive, Confirms Plans to Join Two Divisions," *Wall Street Journal*, 10 November 1997. IBM's device held about 17 gigabytes of data (double what the company had previously offered) and was 3.25 inches in size; the best products from other firms had about 30 percent less storage capacity and were two inches bigger.

40. In July 2002, IBM announced that it was selling 70 percent of its hard-drive division to Hitachi after months of major financial losses ("IBM Says Losses of Hard-Drive Unit Top $500 Million," *Wall Street Journal*, 10 July 2002). Causes for the reversal included the entry of many other firms into the market and diminishing profit margins on hard drives. Nonetheless, IBM's researchers received considerable accolades and rewards for their work. Parkin became an IBM Fellow, a prestigious and unfettered research position, two years after sharing the 1997 Hewlett-Packard Europhysics Prize with Grünberg and Fert. Meanwhile, Virgil S. Speriosu and Bruce A. Gurney, two other IBM scientists who worked with Parkin on spin-valve technology, won an award in 2004 from the Institute for Electrical and Electronics Engineers for their contributions to information-storage technology.

41. Quote from David Awschalom, in Kenneth Chang, "'Spin' Could be Quantum Boost for Computers," *New York Times*, 21 August 2001.

DARPA Supports Spintronics

As products exploiting the GMR effect appeared on the market and more scientists began to do research in what would become known as spintronics, science managers from military laboratories and funding agencies began to take notice. At the same time, major newspapers presented spin-based electronics as a potential new industry paradigm.[42] Journalists struck a tone that comported with a prevailing tendency to predict the end of Moore's Law by hyping the new electronics technology as the "next big thing" for the industry.[43]

One of those monitoring nascent GMR-based spintronics was Stuart Wolf. Trained as a physicist at Rutgers University, Wolf received his doctorate in 1969 and initially researched low-temperature superconductivity in metals.[44] After three years at Case Western Reserve University, Wolf became a staff scientist at the Naval Research Laboratory, where his work on superconductors held interest for a number of defense applications.

In 1993, Wolf accepted a new post as program manager at the Defense Advanced Research Projects Agency. DARPA, of course, was no stranger to supporting research for computer and semiconductor applications; for decades, it had funded major cutting-edge programs in areas such as molecular electronics, integrated-circuit design, and supercomputing.[45] In 1987, the federal government, acting through DARPA, formed the Semi-conductor Manufacturing Technology consortium with several electronics firms. The consortium's purpose was to help the U.S. semiconductor industry retain (some said regain) its competitive edge vis-à-vis Japan's growing strength.[46]

The historical circumstances in which Wolf worked at DARPA were fundamentally different than those experienced by previous research managers. After the end of the cold war, DARPA's managers anxiously sought new missions for the agency. In late 1992, as part of the transition to the new geopolitical environment, the Department of Defense initiated the Technology Reinvestment Project (TRP). Managed by DARPA, the TRP's purpose was to build stronger links between the commercial and military sectors and help the United States reap a greater share of the anticipated

42. For example, William J. Broad, "Using the Spin of Electrons to Make the Smallest Chips Yet," *New York Times*, 6 July 1993; John Markoff, "A Milestone on the Road to Ultrafast Computers," *New York Times*, 6 April 1999.

43. Choi and Mody (n. 16 above) point out that if there is one constant during the last half-century of the electronics industry, it is the prevalence of "radical rhetoric promising rosy futures."

44. Stuart A. Wolf, in a 23 March 2006 interview with W. Patrick McCray.

45. For example, see Alex Roland and Philip Shiman, *Strategic Computing: DARPA and the Quest for Machine Intelligence* (Cambridge, Mass., 2002).

46. DARPA represented the government in this cooperative effort, which directed some $500 million to industry; see Larry D. Browning and Judy C. Shelter, *SEMATECH: Saving the U.S. Semiconductor Industry* (College Station, Tex., 2000).

"peace dividend."[47] The TRP also emerged at a time when established companies like IBM and Bell Labs were cutting support of basic research. The TRP directed over $800 million (with commercial firms providing additional funds) to scores of dual-use technology projects before the program ended in 1996.

One of the modest efforts in the TRP portfolio involved trying to stimulate commercial innovations based on the GMR phenomenon. In 1995, with an initial $5 million from DARPA and matching industry funds, Wolf initiated the GMR Consortium Project. In this program, large companies like Honeywell and newer firms like Nonvolatile Electronics partnered with Wolf's former colleagues at the Naval Research Laboratory to develop a new form of computer memory.

Like GMR-enabled disk drives, magnetic random access memory (MRAM) is based on metallic materials, not semiconductors. Because MRAM devices store data using magnetic-storage elements instead of electrical charge, they have the potential advantage of retaining information even after a computer is switched off. In contrast, data stored in traditional random access memory vanishes when the computer loses power. In principle, computers incorporating MRAM technology could turn on and off instantaneously without having to spend time transferring information from the hard drive to computer chips. MRAM devices would also be less vulnerable to radiation damage, which DARPA found appealing for space-based applications.

Wolf sold his program by pulling an old memory component from a satellite system and taking it into the DARPA offices. "I plopped it on the director's desk," Wolf recalled. "It weighed forty pounds and cost a quarter of a million dollars. I said, 'I'm going to replace this with a fifty-cent chip.'" Wolf's modest program soon expanded into what DARPA initially called the Magnetic Materials and Devices Project.[48] Unsatisfied with this moniker, Wolf suggested a new name—SPin TRansport electrONICS—which he shortened to "SPINTRONICS."[49]

DARPA eventually provided some $100 million to support Wolf's SPINTRONICS program. During its six-year lifetime, four companies (Honeywell, Motorola, IBM, and Nonvolatile Electronics) took part in it.[50]

47. For background on the TRP, see Jay S. Stowsky, "The Dual-Use Dilemma," *Technology Review* 13 (1996): 56–64; and Diane Larriva et al., "A Review of the Technology Reinvestment Project" (Arlington, Va., 1999). This report is available online at http://www.potomacinstitute.org/publications/studies/trpexsum.pdf (accessed 1 October 2008).

48. Stuart A. Wolf and Daryl Treger, "Spintronics: A New Paradigm for Electronics for the New Millennium," *IEEE Transactions on Magnetics* 36 (2000): 2748–51; and Gary A. Prinz, "Magnetoelectronics," *Science* 282 (1998): 1660–63.

49. I am capitalizing SPINTRONICS to designate the specific DARPA program, as distinct from the general field of research.

50. Wolf interview (n. 44 above).

It is important to note that applied physics and engineering, not fundamental research, was the program's primary focus. Through his SPINTRONICS initiative, Wolf helped broker a partnership between commercial and defense interests, an outcome that meshed well with the TRP's goals. However, in order for industry giants in the chip-making business, like Intel, to embrace the potential of spintronics, researchers needed to venture beyond the orderly realm of metals and into the messier world of semiconductors. This would require research into new materials, the development of new instrumentation, and the exploration of the basic physics underlying electron spin.

During the 1990s, experimentalists in the United States, Europe, and Japan made a number of important discoveries that suggested spintronics could perhaps serve as the basis for logic applications (i.e., chips) as well as memory devices. Part of the challenge was to develop new materials that combined selected properties of metallic magnets with semiconductors (which are typically not magnetic). Japanese scientist Hideo Ohno helped establish a breakthrough in this area. In the late 1980s, he took a leave of absence from his professorial duties at Hokkaido University to spend a year and a half as a visiting researcher at IBM's Yorktown Heights laboratory, where a longstanding interest in materials for new computer chips existed.

At IBM's lab in New York, Ohno and his colleagues decided to expand their research on semiconductors and try "something wild and impossible"—to make a magnetic semiconductor.[51] When asked if he was aware of developments related to GMR and MRAM while doing his research, Ohno's comment—"I didn't pay much attention to what the metals people were doing"—illustrates the gap that existed between researchers who studied metallic systems and those interested in semiconductors. Ohno's research on magnetic semiconductors helped link these two branches of solid-state physics.

Stephen von Molnar, a long-time scientist at IBM, encouraged Ohno's research. Von Molnar—an older solid-state physicist and expert in magnetic materials—Ohno, and postdoctoral-student Hiro Munekata started experimenting with different materials. Eventually, they used molecular beam epitaxy to fabricate the first ferromagnetic semiconductor by introducing manganese, which is magnetic, into the semiconductor indium arsenide.[52] Their work provided a proof-of-concept accomplishment that revealed the possibility of integrating electronics and magnetics.[53]

51. Hideo Ohno, in a 22 March 2006 interview with W. Patrick McCray.

52. Reported in H. Munekata et al., "Diluted Magnetic III-V Semiconductors," *Physical Review Letters* 63, no. 17 (1989): 1849–52.

53. Ohno returned to Japan in 1990, where he continued his research on magnetic semiconductors in the Department of Electronics at Tohoku University. In 1996, Ohno and his colleagues in Japan announced that they had built novel nanostructured materials by introducing manganese into gallium arsenide, a more traditional semiconducting

Another series of important developments related to semiconductor-based spintronics arose from the research activities of David Awschalom. After earning his doctorate from Cornell University in 1983, Awschalom, the son of a medical physicist, took a research position at IBM's Yorktown Heights lab, where he worked with scientists like Ohno and von Molnar. Awschalom directed his own research program toward the fundamental physics and development of experimental techniques to explore electron spin and charge dynamics at the nanoscale. In 1991, during a period of decline in support for physics research at IBM, he moved to an academic post at the University of California, Santa Barbara, where he began to tackle problems standing in the way of exploiting electron spin and its quantum-mechanical properties in semiconductors.[54]

One barrier to using electron spin in logic devices is coherently transferring spin (in the same spin-aligned state) between two different semiconductor materials; another is maintaining the electrons in a desired spin state long enough for something useful to be done with them.[55] In 1997, Awschalom and his research team made an unexpected discovery when they learned that they could create and observe electron spins in semiconductors, which remained coherent for unexpectedly long times. Subsequent work by Awschalom's group showed that they also could transport a "spin packet" of electrons over a distance similar to what might be needed in an actual device.[56] Laboratory demonstrations like these suggested that engineers could perhaps develop logic devices based on spin-polarized charge carriers.[57]

As a DARPA research manager, Stuart Wolf continued to monitor new developments in semiconductor-based spintronics as well as ongoing work with metals systems. Encouraged by what he saw, Wolf proposed a more ambitious research effort in late 1999 called SPINS (an acronym for "Spins in Semiconductors"). Unlike the initial SPINTRONICS program, which was applications-oriented, Wolf promoted SPINS primarily as a basic research program. With annual funding from DARPA of about $30 million, SPINS represented a considerable investment in what was still esoteric solid-state physics and materials-science research.[58]

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material. Not only did this new alloy display ferromagnetism, but it did so at relatively high temperatures, whereas Ohno's first attempts required cryogenic conditions. See H. Ohno et al., "(Ga, Mn)As: A New Diluted Magnetic Semiconductor Based on GaAs," *Applied Physics Letters* 69 (1996): 363–65.

54. This information comes from the Awschalom interviews (n. 37 above). For IBM, see Barnaby J. Feder, "Eureka! Labs with Profits," *New York Times*, 9 September 2001.

55. Michael L. Roukes, "Electronics in a Spin," *Nature* 411 (2001): 747–48.

56. J. M. Kikkawa and D. D. Awschalom, "Lateral Drag of Spin Coherence in Gallium Arsenide," *Nature* 397 (1999): 139–41.

57. Michael Oestriech, "Injecting Spin into Electronics," *Nature* 402 (1999): 735–36.

58. Wolf interview (n. 44 above). Also, information on DARPA budgets comes from annual declassified reports, available at http://www.darpa.mil/body/dar_archives.html

In January 2000, 175 scientists, research managers, and graduate students convened in Santa Barbara for the launch of Wolf's SPINS program.[59] The meeting introduced researchers and students thinking of entering spintronics to the current state of the field. Representatives from the navy and the army, for instance, summarized recent efforts in quantum computing, nano-magnetics, and spin-based devices. Attendees also learned how to apply for future funding from Wolf's new initiative.

Wolf and his colleagues organized several more annual workshops for people involved or interested in spintronics. The influx of new funding certainly helped attract some senior researchers to the field and provided support for graduate and postdoctoral students. In a very real sense, military funding and interest, coupled with exciting physics and potential device applications, helped knit a diverse group of researchers into an international research community. This community, based on the people who attended the yearly DARPA events, was a hybrid, consisting of university-based researchers, scientists from government laboratories, and representatives from the electronics industry.[60] It was also highly interdisciplinary, bringing together physicists, materials scientists, chemists, and engineers who had experimental as well as theory-oriented backgrounds. Finally, in terms of age and experience, conference attendees included graduate students and postdoctoral researchers, along with tenured faculty members.

Publication and patenting statistics suggest how DARPA's support helped fuel interest in spintronics as a research field and arena for future commercialization.[61] From 1988 to 1993, for instance, researchers typically published fewer than a hundred articles per year on any experimental or theoretical aspect related to spintronics. By 1996, as IBM and other companies rushed to perfect GMR-based devices, the publication rate had almost quadrupled. After five more years, with Wolf's SPINS program well under way, the output had doubled to over 800 papers annually. Similar trends can be seen in patenting, with a major increase occurring around 1999.[62] The vast majority of both patenting and publishing activity took

(accessed 30 April 2008). Obtaining exact budget details is complicated by the fact that funding for spintronics, in general, came from several programs within DARPA.

59. From "Agenda, Presentations, and List of Attendees at the Spins in Semiconductors (SPINS) Workshop," 5–7 January 2000, Santa Barbara, California. Originals graciously provided by Professor Michael Flatté (copies in author's possession).

60. For instance, the first SPINS meeting held in January 2000 had 175 attendees: 95 were from universities, 38 from the private sector, and 42 from government institutions such as national laboratories, NASA, and defense agencies.

61. My conclusions are based on an in-depth examination of publishing, patenting, and collaboration trends within the spintronics community. This work was carried out in 2006 by Timothy Lenoir and Eric Gianella of Duke University, with input from the author and Cyrus Mody.

62. The majority of patents were related to disk-drive technologies that were likely fueled by IBM's innovations in 1997. The lag between publication surges and patent in-

place in Japan and the United States, especially California. As one would expect, the degree of international collaboration also grew markedly during this time, as researchers from Europe, Japan, and the United States did lab work and coauthored articles together. The general pattern of increase in publications and patents throughout the 1990s coincided with the growth of DARPA funding and the development of new magnetic data-storage technologies. While direct causality cannot be assumed, it is reasonable to conclude that the funding Wolf and his colleagues helped make available played a not-insignificant role in fostering the growth of the spintronics research community.

Using Spintronics to Promote Nanotechnology

By 2000, science journalists and corporate managers were paying considerable attention to research on electron spin. Major journals such as *Nature*, *Science*, and *Physics Today*, for instance, highlighted the lab results produced by Awschalom and his students with feature articles and colorful covers. In April 2000, *Nature* reviewed the major developments that had taken place in both metals- and semiconductor-based spintronics over the past several years. In doing this, the journal framed its story in a familiar context of speculation and hyperbole. Industry giants like IBM and Motorola, it noted, were planning to spend up to $100 million to fund the work of so-called "spin doctors" who were "plotting a revolution in electronics." This investment, spintronics advocates predicted, might reinvent the electronics industry and produce devices with "completely new kinds of functionality" based on "genuine quantum electronics."[63]

The interest and support that DARPA and companies like IBM gave to spintronics (and the media attention accompanying the burgeoning field) coincided with a movement under way in the United States and overseas to generate political support for a broader research and development effort in nanotechnology. Advocates of national policies to support nanotechnology deployed the economic importance of "nanoelectronics," and the commercial success of spintronics in particular, to support their broader agenda.

In the 1990s, funding for biomedical research in the United States soared, while corporate and federal support for the physical sciences stagnated. Advocates of a national nanotechnology program saw an opportunity to redirect funding into relatively neglected areas of research like solid-state physics, engineering, and materials science. To supporters, nanotechnology represented a new frontier that, like information technologies, could eventu-

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creases can be explained by the fact that the time to prosecute a patent in the United States is typically about two-to-three years.

63. All quotes are from Philip Ball, "Meet the Spin Doctors . . .," *Nature* 404 (2000): 918–20.

ally become a substantial part of the U.S. economy.[64] While what became known as the National Nanotechnology Initiative (NNI) ultimately funded a considerable amount of basic physics, chemistry, and biology research, potential applications and issues of market competitiveness initially captured the attention of many policy makers.

In the late 1990s, nanoelectronics figured prominently in the strategizing of scientists and science managers who supported the NNI. Between 1997 and 1999, for instance, the National Science Foundation organized a series of comprehensive studies to evaluate possible research opportunities in nanotechnology.[65] After scientists from academic and corporate labs surveyed the current state of research in nanoelectronics and related materials, their reports and presentations conveyed a common story: at some time during the next ten-to-fifteen years, the semiconductor industry would encounter serious technical barriers to continued miniaturization and performance. The path to a replacement technology was unknown, scientists and engineers said. Without major investment in new technologies for the computer and semiconductor industries, broader U.S. economic interests could suffer.[66] Along with medicine, energy, and national security concerns, these studies presented the needs of U.S. electronics and computer firms as one of the critical societal and economic applications of nanotechnology.

In framing their evaluation, scientists and engineers from the academy and industry cited how U.S. companies had rapidly capitalized on GMR—a basic physics discovery made in European labs. For example, Stanley Williams (a scientist at Hewlett-Packard Laboratories), Paul Alivisatos (a Cal-Berkeley chemist), and Mihail Roco (an NSF program manager) coedited a 1999 study that presented a "vision for how the nanotechnology community—Federal agencies, industries, universities, and professional societies—can more effectively coordinate efforts to develop a wide range of revolutionary commercial applications."[67] GMR, according to the report, was "the most recent success story" in nanoelectronics, and it had helped transform a market worth well over $30 billion annually.[68] Reports and studies such

64. Thomas Kalil, in a 21 June 2006 interview with W. Patrick McCray.

65. These studies were done under the auspices of the World Technology Evaluation Center (WTEC). This process is described in McCray, "Will Small Be Beautiful?" (n. 7 above). Examples of these nano-related WTEC reports include: Richard W. Siegel, Evelyn Hu, and Mihail C. Roco, eds., *WTEC Workshop Report on R&D Status and Trends in Nanoparticles, Nanostructured Materials, and Nanodevices in the United States* (Baltimore, 1998); Richard W. Siegel, Evelyn Hu, and Mihail C. Roco, *Nanostructure Science and Technology: A Worldwide Study* (Baltimore, 1999); and Roco, Williams, and Alivisatos (no. 6 above).

66. See, for instance, the material in the technical summary on nanoelectronics and computer technology in Roco, Williams, and Alivisatos.

67. From a 27 September 1999 letter by Neal Lane (President Clinton's assistant to the president for science and technology), which is included at the beginning of the report; see ibid., 3.

68. Ibid., 78.

as these also highlighted DARPA's investments in applied research for MRAM and some of the initial government support for innovative research into semiconductor spintronics. Future federal funding for nanoelectronics, these experts said, could lead to industry "paradigm shifts" and "fundamentally new information processing architectures."[69]

These surveys and reports provided a platform for the next stage in formulating a national nanotechnology policy, one which gave nanoelectronics a central place. In early 1999, when proposals for the NNI moved to the White House, one can discern the intersecting interests of university-based scientists and the semiconductor industry. Thomas Kalil, President Clinton's deputy assistant for technology and economic policy, was one of the people the research community looked to for support. Kalil was predisposed to understanding the needs of the semiconductor industry, as he had previously worked in Washington for Dewey Ballantine, a firm that represented the semiconductor industry.

After he moved to the White House, Kalil retained his interest in electronics and computers; one of his major initiatives was the Next Generation Internet. Shaped by Kalil and proposed by the Clinton administration in 1996, this program aimed to improve business and citizen access to information technology. After the Clinton administration launched the Next Generation Internet program, Kalil was looking for another technology issue to promote when, as he recalled, he "stumbled across nanotechnology."[70] Kalil, in turn, became a key contact for the NNI inside the White House. Semiconductor manufacturers were the only identifiable corporate group that lobbied directly for the National Nanotechnology Initiative. Kalil, who was able to facilitate this interaction through his former industry connections, solicited letters from them in support of the NNI.[71]

Political interest in nanoelectronics continued as discussion about the NNI moved from the White House to Congress. In June 1999, when Congress convened a hearing to examine the state of nano-related research and

69. Ibid., 79.

70. Kalil interview (n. 64 above). See also Patrick Windham, "TPI Working Paper: The U.S. National Nanotechnology Initiative" (Washington, D.C., 2001). My thanks to Thomas Kalil for providing me with a copy of this white paper, which is included as chapter 4 in *Public Policies and the Emergence of High-Technology Sectors*, a January 2001 report. That report's executive summary is available at http://www.technopoli.net/2001execsum.pdf (accessed 30 April 2008). Kalil's own recollections appear in Neal Lane and Thomas Kalil, "The National Nanotechnology Initiative: Present at the Creation," *Issues in Science and Technology*, Summer 2005, 49–54.

71. From page 7 of Windham, "TPI Working Paper," who based his conclusion on discussions with several key people in the Clinton administration, which presumably included Kalil. After leaving the White House, Kalil maintained that one of the NNI's major accomplishments would be to help the U.S. electronics industry's continuation of Moore's Law with nanoelectronics; see Lane and Kalil, "The National Nanotechnology Initiative."

its future prospects, electronics figured prominently. For instance, Nobel laureate Richard Smalley testified that within twenty years, the current technological paradigm of silicon microelectronics would be supplanted by a "true nanoelectronics of vastly greater power and scope."[72] Smalley and other expert witnesses made it clear to Congress that nanoelectronics (and, by virtue of association, the health of the electronics industry) stood to benefit if nanotechnology became a major national initiative.[73]

Not surprisingly, nanoelectronics emerged as a "priority research area" in the NNI's initial formulation.[74] Advocates for nanotechnology presented spintronics-based devices like GMR-based hard drives as proof of the commercial benefits to come if basic research was aggressively supported. More generally, nanotechnology's supporters pointed to the success stories of Silicon Valley and the microelectronics industry as evidence that future-oriented research and development in nanoelectronics was worth funding, even if this was still in an embryonic state. The recent history of nanoelectronics, particularly spintronics, became a powerful example to invoke when advocating for research funding. The return on this national investment would enhance future economic competitiveness and new scientific discoveries.

72. Page 9 of U.S. House of Representatives Committee on Science, "Nanotechnology: The State of Nano-Science and Its Prospects for the Next Decade" (Washington, D.C., Committee on Science, U.S. House of Representatives, Subcommittee on Basic Research, 1999). Smalley's correspondence with NNI advocates in 1999 explicitly discusses the importance of describing the "impact of Giant Magneto-resistance on non-volatile memory"; see 6 May 1999 e-mail from Mihail Roco to Smalley, box 31, folder 7, Richard Smalley Papers, Chemical Heritage Foundation, Philadelphia. My thanks to Cyrus Mody for sharing copies of this with me.

73. In the late spring of 1999, Neal Lane, Clinton's science advisor, wrote two memos discussing interagency research priorities. Interestingly, the first memo (dated 22 April 1999) listed nanotechnology last out of eleven initiatives; in the second memo (dated 8 June 1999), nanotechnology had moved to number one. These memos were available in May 2007 at http://www.ostp.gov/html/996_3_2.html and http://www.ostp.gov/html/0076.html, but they are no longer posted online as of 30 April 2008. Copies in author's files.

74. From pages 28–30 of "National Nanotechnology Initiative: The Initiative and Its Implementation Plan" (Washington, D.C., U.S. House of Representatives Committee on Science, Subcommittee on Nanoscale Science, Engineering, and Technology, 2000). In 2004, even as the House Appropriations Committee considered cutting the NSF's budget, it singled out nanoelectronics as an area that still warranted high levels of support to "enable continued productivity growth in the information economy." See Richard M. Jones, "House Appropriations Bill Recommends Cut in FY 2005 NSF Funding," *FYI: The AIP Bulletin of Science Policy News* 99 (23 July 2004), available at http://www.aip.org/fyi/2004/099.html (accessed 30 April 2008).

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A tour de force of experimental physics, Fert and Grünberg built their 1988 discovery of GMR from several heterogeneous elements. These included new tools and techniques such as molecular beam epitaxy, which researchers in the electronics industry had perfected years earlier. These new instruments enabled the precise fabrication and characterization of novel materials, another key ingredient. Intellectually, the foundational knowledge for spintronics came from a wide array of fields, including solid-state physics, superconductivity, metallurgy, and magnetics. Companies like IBM went on to commercialize the Nobel Prize–winning discovery after extensive engineering research efforts. The appearance of commercial products incorporating GMR-based technologies coincided with the emergence of spintronics as a "new" research field, one stimulated to a large degree by military agencies like DARPA and the Naval Research Laboratory. Even though IBM sold its increasingly unprofitable hard-drive business to Hitachi in 2002, the company's efforts in the late 1990s had created, according to one journalist, "the most important commercial spintronics device on the market."[75] Articles in newspapers, trade publications, and scientific journals stimulated additional interest in spintronics and facilitated the field's expansion. In a broader sense, the discovery of GMR and its successful commercialization provided nanotechnology advocates with a clear success story that helped bolster their arguments for a major new national effort in this area.

The story of spintronics invites scholars to reexamine some key questions in the history of technology. The first of these concerns the nature of contemporary knowledge production, especially as new patterns of collaboration emerged after the end of the cold war.[76] As a recent essay noted: "Nanoscience is the first full embodiment of post-academic science. It is more a 'how' than a 'why.'"[77] Consequently, this new approach to producing knowledge has helped engender "new types of social arrangements . . . that shape the way in which research is conducted and that represent a radical culture change."[78]

Already-established modes of support for research and development reflected this realignment, especially after the cold war ended. For instance,

75. Barnaby J. Feder, "IBM Joins Stanford to Find Uses for Electron Spin," *New York Times*, 26 April 2004.

76. What John Ziman (n. 20 above) calls "post-academic science" is similar to what Michael Gibbons and his coauthors label "Mode-2" research in *The New Production of Knowledge* (London, 1994).

77. Thomas Vogt, Davis Baird, and Chris Robinson, "Opportunities in the 'Post-Academic' World," *Nature Nanotechnology* 2 (2007): 329–32, quote on 329.

78. Ibid.

the military had long nurtured research in materials science and solid-state physics, areas that were later central to the development of spintronics. As scholars such as Tom Misa, Paul Forman, and Christophe Lécuyer have shown, military funding was also a potent stimulant to the growth of the electronics industry in the United States.[79] National security and economic competitiveness needs motivated this largesse, which supported a great deal of basic and applied research.

After the cold war ended, military agencies continued to help foster new scientific fields, albeit sometimes through industry alliances like the SPINTRONICS initiative or hybrid government–university–industry programs like SPINS. Research managers such as Stuart Wolf, acting as institutional entrepreneurs, built programs that melded military funding with corporate investment and goals. Moreover, the support DARPA and industry firms provided to spintronics-based science served multiple interests. Like the "quantum electronics" of the 1950s, spintronics blended fundamental research with the imperative to produce applications and devices. The case of spintronics and federal support for nanotechnology in general are suggestive examples of what sociologist Fred Block calls the "hidden developmental state" through which the U.S. government has supported the private sector's commercialization of new technologies.[80]

Even though it helped catalyze the field of spintronics, DARPA did not remain a long-term supporter. In 2001, when a new presidential administration took power, the agency's priorities shifted to new areas such as biological-oriented research and, after the terrorist attacks of 11 September 2001, projects with more direct ties to national security.[81] As DARPA retreated from spintronics, university-based researchers increasingly looked to corporate partnerships for funding.[82] These endeavors provided firms

79. Misa (n. 17 above); Paul Forman, "Into Quantum Electronics: The Maser as 'Gadget' of Cold War America," in *National Military Establishments and the Advancement of Science and Technology*, ed. Paul Forman and José Sánchez-Ron (London, 1996), 261–326; see also Lécuyer (n. 10 above).

80. Fred Block, "Swimming against the Current: The Rise of a Hidden Developmental State in the United States," *Politics and Society* 36 (2008): 169–206.

81. The persuasiveness of program managers who generate interest and support for particular lines of research strongly influences which research DARPA supports. As Wolf recalled: "Spintronics didn't have a champion after I left." See Wolf interview (n. 44 above), as well as personal communications (10 June 2007) between Wolf and the author.

82. In 2004, for example, the Semiconductor Industry Association's board of directors announced a new Nanoelectronics Research Initiative (NRI), which combined cash and equipment contributions from six semiconductor corporations, including IBM and Intel. The largest share of funding went to establish three university-based research centers in California, New York, and Texas. Analysts estimated that the total assets for the three centers equaled some $750 million, with the six companies directly contributing $40 million. See George Bourianoff and Thomas Theis, "NRI Motivation, Vision, and Proposed Plan," a 2005 industry white paper of the Semiconductor Research Corpora-

lacking in-house basic research programs the opportunity to outsource work to faculty and students at campus labs. For example, Intel contributed millions of dollars of funding—a relatively small sacrifice, to be sure, for the giant company—to university-based research in nanoelectronics and quantum computing.[83] Seen this way, the emergence of such corporate–academic partnerships represented a continuing realignment of industry's support for research and development. The type of knowledge production these partnerships supported, driven by utility and practical problems, aligns with an interpretation that views modern basic research as a "wealth-creating technoscientific motor for the whole economy."[84]

The story of spintronics can also shed light on debates that have reemerged among scholars about some major historiographical questions. One of these concerns the validity of the linear model of research. Presented most famously by Vannevar Bush in his 1945 report, *Science: The Endless Frontier*, the most basic form of the model supposes a direct path from scientific discovery to application. While historians have examined, refined, and problematized it for decades, this model remains a point of contention and scholarly inquiry.[85] To a first order of approximation, the case of spintronics appears to lend credence to the traditional linear model, which posits science as a prime mover for technological applications. As members of the 2007 Nobel committee saw it, an unexpected laboratory discovery inspired IBM's industrial research and successful exploitation of the phenomenon and consequently billions of computers and iPods followed. The full story, of course, was much more complex, revealing the interplay among basic science, instrumentation, federal policy, industrial research, and commercial goals. One cannot help but conclude that the "simple" linear model, when examined closely enough, is anything but.

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tion that was posted, as of May 2006, at http://www.src.org/nri/pubs.asp. The report is no longer available online as of 30 April 2008, but a copy is in the author's files. The actual title of the initiative is somewhat confusing: some early documents on the NRI site refer to the "N" in NRI as "nanotechnology"; in others, it stands for "nanoelectronics." By 2007, the latter had become the preferred term.

83. For Intel, investment in long-term research was a departure for the firm. In the past, Intel managers stated that the company's lack of in-house basic research was an ingredient for its success. Gordon Moore, Intel's legendary founder, once boasted that the company wasn't into "exploring for curiosity's sake. We were doing what was necessary to solve particular problems." From page 331 of Robert Buderi, *Engines of Tomorrow: How the World's Best Companies Are Using Their Research Labs to Win the Future* (New York, 2000). See also Bassett (n. 10 above).

84. See Ziman (n. 20 above), 73; and Ann Johnson, "The End of Pure Science? Science Policy from Bayh-Dole to the National Nanotechnology Initiative," in *Discovering the Nanoscale*, ed. Alfred Nordmann, Joachim Schummer, and Davis Baird (Amsterdam, 2004), 217–30, which frames the entire nano-enterprise in the context of this new regime.

85. See, for instance, recent essays by Glen Asner and David Edgerton, as well as David Hounshell's commentary, in Karl Grandin, Nina Wormbs, and Sven Widalm, eds., *The Science–Industry Nexus: History, Policy, Implications* (Sagamore Beach, Mass., 2004).

The manner in which journalists and scientists interpreted Fert and Grünberg's discovery also speaks to recent questions about the boundary between, and conflation of, science and technology. In a recent essay, Paul Forman provocatively challenged historians to rethink the relation between these.[86] While I do not agree entirely with claims about the primacy of technology over science as a signifier or symptom of postmodernity, spintronics (and, perhaps more importantly, how participants view its history) illustrates how science can be conflated with technological applications.[87] For example, key policy makers argued in support of increased funding for nanoscience, yet Neal Lane, Clinton's science advisor, later acknowledged that their prevailing objective was establishing new policies for *technology*.[88] Major newspapers and science magazines have presented research results from the spintronics community with a strong bias toward future commercial applications. A substantial portion of all coverage of nanoelectronics (and nanotechnology in general) in venues such as the *New York Times* appears in the business, as opposed to the science, section.[89] Even Albert Fert, interviewed after learning he would share the Nobel Prize, remarked: "These days when I go to the grocer and see him type on a computer, I say 'Wow, he's using something I put together in my mind.'"[90]

Regardless of how future debates about the relation between science and technology develop, it is clear that newly emerging research communities, such as those exploring nanoscale phenomena, are doing studies fully mediated and pervaded by technology.[91] And by considering new fields like spintronics, historians of technology have an opportunity to engage once again with one of the defining, and still persistent, questions of our field.

86. Forman, "The Primacy of Science in Modernity" (n. 21 above).

87. The astute reader may have noticed that debates about the continued validity of the traditional linear model are at odds, in some ways, with recently raised questions about the postmodern primacy of technology over science; in other words, the validity of a linear model, however simplified, that has science leading to technology could be seen as contradicting claims that technology has subordinated science. My point here, obviously, is not to resolve any contradiction, but to highlight how the case of spintronics lets historians address larger issues.

88. Davis Baird and Ashley Shew, "Probing the History of Scanning Tunneling Microscopy," in *Discovering the Nanoscale: A Reader of Workshop Manuscripts; from an International Conference at Darmstadt Technical University, October 9–12, 2003*, ed. Davis Baird et al. (Darmstadt, 2003), 10.

89. Ronald Kline notes a similar example in his excellent "Cybernetics, Management Science, and Technology Policy: The Emergence of 'Information Technology' as a Keyword," *Technology and Culture* 47 (2006): 513–35. Also worth noting is Ronald Kline's rejoinder to Forman in "Forman's Lament," *History and Technology* 23 (2007): 160–65.

90. Overbye (n. 1 above).

91. I would like to thank Norton Wise for sharing his comments from the 2007 Annual Meeting of the Society for History of Technology, which cover this point. (His comments were titled "Science *Is* Technology?" and were delivered in a session on 20 October 2007 devoted to addressing the points Paul Forman raised in his 2007 essay, "The Primacy of Science in Modernity.")