The changing structure of American innovation: Cautionary remarks for economic growth

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Abstract

A defining feature of modern economic growth is the systematic application of science to advance technology. However, despite continuous progress in scientific knowledge, recent productivity growth in the U.S. has been disappointing. We review major changes in the American innovation ecosystem over the past century and note that the past three decades have been marked by a growing division of labor between universities focusing on research and large corporations focusing on development. Knowledge produced by universities is not often in forms that can be readily digested and turned into new goods and services by companies, especially as large companies themselves withdraw from research. Small firms and university technology transfer offices cannot fully substitute for corporate research, which integrated multiple disciplines and components at the scale required to solve significant technical problems. Therefore, whereas the division of innovative labor may have raised the volume of science by universities, it also slowed, at least for a period of time, the transformation of that knowledge into novel products and processes.

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1 Introduction

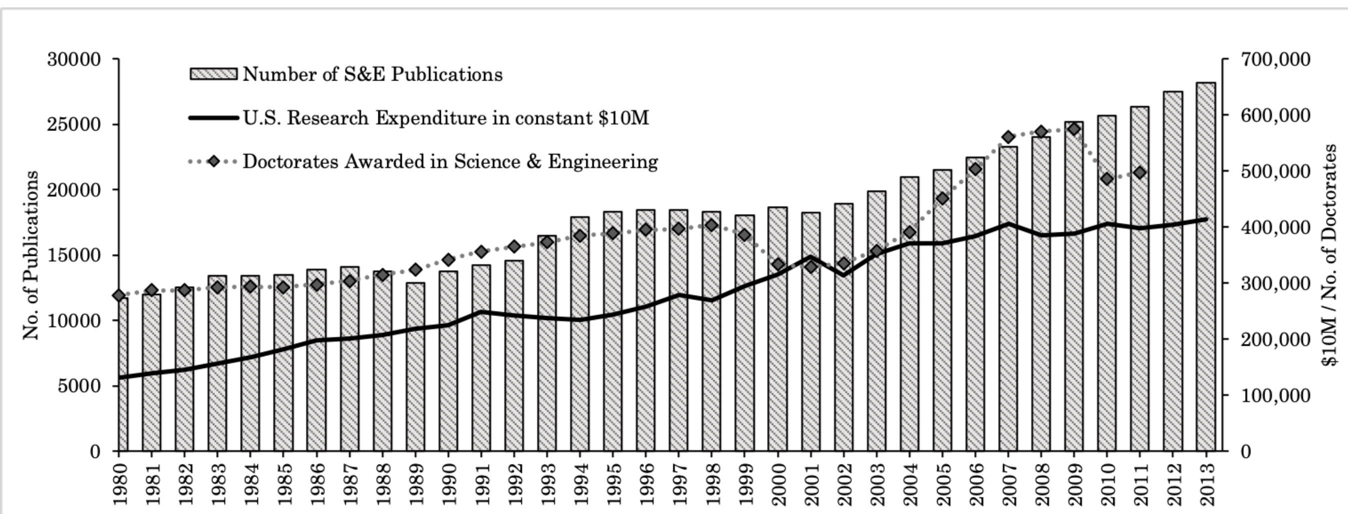
A defining feature of modern economic growth is the systematic application of science to advance technology. Many innovations that spurred economic growth in the twentieth century, including synthetic fiber and plastics, integrated circuits and gene therapy, originated from advances in the natural sciences, engineering and medicine. Science, by producing "a potential for technology far greater than existed previously," clearly distinguishes modern economic growth from previous economic epochs (Kuznets, 1971).

However, despite continued increases in the quantity of scientific knowledge produced shown in figure 1, productivity growth in most advanced economies has stagnated in recent decades in comparison to a "golden age" in the mid-twentieth century. Using data from the United States, Gordon (2016) shows that real GDP per hour (i.e., labor productivity) grew substantially in the middle of the twentieth century, from 1.79 % per year during 1870-1920 to 2.82 % per year during 1920-1970. However, in the most recent period (1970-2014), productivity grew by a modest 1.62 % per year. Gordon decomposes this productivity growth into three components: (i) rising educational attainment, (ii) rising amount of capital input per worker hour (capital deepening), and (iii) total factor productivity (TFP) growth (commonly used by macroeconomists as a proxy for the contribution of innovation to economic growth). He shows that while rising educational attainment and capital deepening contributed approximately the same to productivity growth in all three periods, the impact of TFP growth was much larger during the 1920-1970 period, nearly three times the growth rate registered in the two other periods. He concludes that productivity rose in 1920-1970 largely because of significant technological progress, but more recently technical advance has been much less potent in spurring growth. This slowdown is surprising given the continued expansion of scientific input (measured in terms of research dollars spent) and output (measured by academic articles published) from American academia.

Indeed, Bloom et al. (2017) present evidence across a number of sectors showing that research productivity in the U.S. has declined since the 1970s, and argue that economic growth has been sustained principally through increasing research effort. For instance, maintaining the exponential growth in semiconductor performance (otherwise known as "Moore's Law") in 2014 required around

18 times the number of researchers it used to take in 1971.[1] While growth rate for yields per acre for corns, soybeans, cotton, and wheat have averaged around 1.5%, the number of researchers in the agriculture sector has grown by a factor between 3 (wheat) and 25 (soybeans). This translates to a research productivity decline of about 4 to 6 percent per year. In the life sciences, the number of researchers has been rising by 6% annually, while research productivity measured by the discovery of new molecular entities per number of researchers has been falling by 3.5% per year. The authors also link clinical trials publications to specific diseases and find that average life expectancy extensions achieved by such trials decreased from over eight years to just over a year between 1985 and 2006. Finally, based on firm-level data from Compustat covering the period 1980-2015, the authors show that research productivity, measured by averages of sales, market capitalization, and employment per R&D expenditure, declined at a rate of 9 percent per year.

Figure 1: U.S. Scientific Investment and Output, 1980-2013



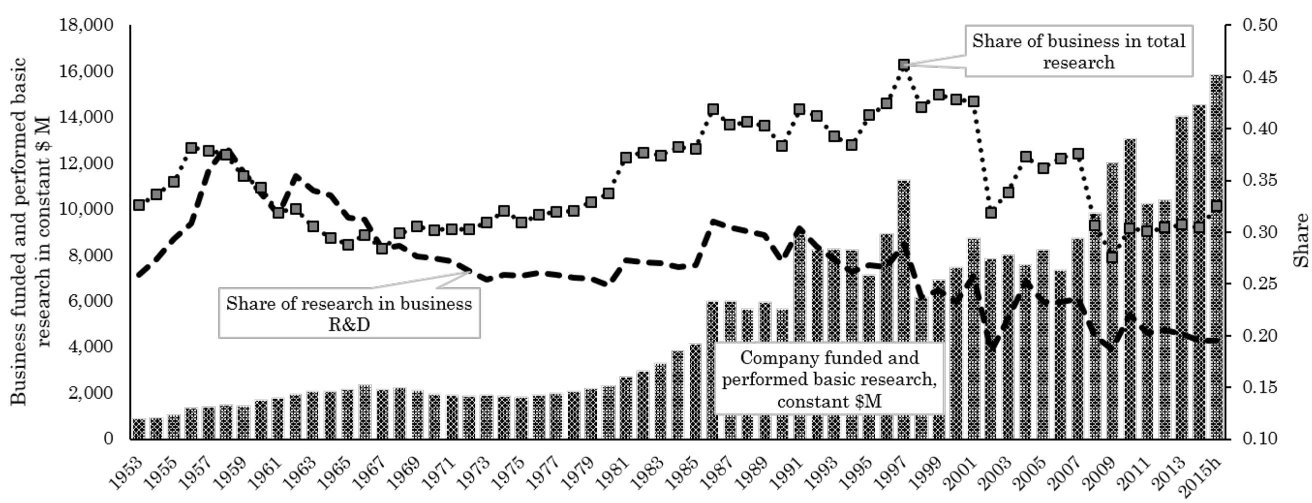
*Notes:*Doctorates Awarded in S&E are calculated from the NSF's Survey of Earned Doctorates and excludes degrees in the Social sciences. Number of S&E Publications are calculated from the Clarivate Web of Science platform and includes all scientific articles in the Science Citation Index (SCI) Collection with a U.S. author from 1980 to 2015. U.S. Research Expenditure figures are calculated from the *National Patterns of R&D Resources: 2014-15 Data update. NSF 17-311.* tables and includes both basic and applied research expenditure. Figures are adjusted to 2016 dollars using GDP deflator from the World Bank National Accounts dataset.

Gordon attributes the rapid pace of technological progress in 1920-1970 to the development and extension of earlier fundamental technologies, such as the internal combustion engine and electricity. This process, which was often accompanied by important advances in science and engineering, was largely carried out by researchers working in corporate labs, which, by the 1920s, had replaced individual entrepreneurs as the primary source of American invention. As Gordon (2016, p.571-572)

[1]Number of researchers is measured as semiconductor firm R&D divided by the average wage of high-skilled workers.

writes: "Much of the early development of the automobile culminating in the powerful Chevrolets and Buicks of 1940-41 was achieved at the GM corporate research labs. Similarly, much of the development of the electronic computer was carried out in the corporate laboratories of IBM, Bell Labs, and other large firms. The transistor, the fundamental building block of modern electronics and digital innovation, was invented by a team led by William Shockley at Bell Labs in late 1947. The corporate R&D division of IBM pioneered most of the advances of the mainframe computer era from 1950 to 1980. Improvements in consumer electric appliances occurred at large firms such as General Electric, General Motors and Whirlpool, while RCA led the early development of television."

Figure 2: Business funded and performed research in the United States, 1953-2015



Notes: Data for this graph is sourced from the *National Patterns of R&D Resources: 2014-15 Data update. NSF 17-311.* from the National Science Foundation, National Center for Science and Engineering Statistics. 2017. Arlington, VA. Available at https://www.nsf.gov/statistics/2017/nsf17311/.

By the 1980s, however, many corporations began to look to universities and small start-ups as a source of ideas and new products.[2] As large corporations' reliance on externally sourced inventions grew, many leading Western corporations began to withdraw from scientific research (Mowery, 2009; Arora et al., 2018). Some corporate labs were shut down and others spun-off as independent entities. Bell Labs had been separated from its parent company AT&T and placed under Lucent in 1996; Xerox PARC had also been spun off into a separate company in 2002. Others had been downsized: IBM under Louis Gerstner re-directed research toward more commercial applications in the mid–90s

[2]A good example is IBM, which on November 6, 1980 signed a contract with a then small firm, Microsoft, for the development of its operating systems. Microsoft itself developed its operating system (eventually named the IBM PC-DOS) building on the operating system of another small company, Seattle Computer Products.

(Pisano, 2010).[3] A more recent example is DuPont's closing of its Central Research & Development lab in 2016. Established in 1903, DuPont Central R&D served as a premiere lab on par with the top academic chemistry departments. In the 1960s, the central R&D unit published more articles in the *Journal of the American Chemical Society* than MIT and Caltech combined. However, in the 1990s, DuPont's attitude toward research changed as the company started emphasizing business potential of research projects. After a gradual decline in scientific publications, the company's management closed the Experimental Station as a central research facility for the firm after pressure from activist investors in 2016.

These examples are backed by systematic evidence. NSF data indicate that share of research (both basic and applied) in total business R&D in the U.S. fell from about 30% in 1985 to below 20% in 2015 (figure 2). The figure also shows that the absolute amount of research in industry, after increasing over the 1980s, barely grew over the 20 year period between 1990 to 2010. Other data show the same decline. Utilizing data on scientific publications, Arora et al. (2018) show that the number of publications per firm fell at a rate of 20% per decade from 1980 to 2006 for R&D performing American listed firms. The authors also find that the drop is even more dramatic for established firms in high quality journals: Limiting their analysis to articles within the top quartile of Journal Impact Factor, the magnitude of the drop increases to over 30%. Large firms' withdrawal from science can also be gleaned from the list of R&D 100 awards winners: Fortune 500 firms won 41% of the awards in 1971, but only 6% in 2006 (Block and Keller, 2009). Over the same period, total industry R&D and patenting grew steadily, as did university performed research (see figure 6 below). This evidence points to the emergence of a new division of innovative labor, with universities focusing on research, and large firms focusing on development and commercialization, with spinoffs, startups, and university technology licensing offices responsible for connecting the two.

In this chapter, we suggest that this division of innovative labor may not have lived up to its promise. The translation of scientific knowledge generated in universities to productivity enhancing technical progress has proved to be more difficult to accomplish in practice than expected. Spinoffs, startups, and university licensing offices have not fully filled the gap left by the decline of the corporate

[3] According to Ralph Gomory (former research director and Senior Vice President for Science & Technology at IBM), management downplayed the Gerd Binnig and Heinrich Rohrer's scanning tunneling microscope to investors, (which had earned them the Nobel prize in physics in 1986) for fear of a drop in share prices.

lab. Corporate research has a number of characteristics that make it very valuable for science-based innovation and growth. Large corporations have access to significant resources, can more easily integrate multiple knowledge streams, and their research is directed toward solving specific practical problems, which makes it more likely for them to produce commercial applications. University research has tended, more so than corporate research, to be curiosity-driven rather than mission-focused. It has favored insight rather than solutions to specific problems, and partly as a consequence, university research has required additional integration and transformation to become economically useful. This is not to deny the important contributions that universities and small firms make to American innovation. Rather, our point is that large corporate labs may have distinct capabilities, which have proved to be difficult to replace. Further, large corporate labs may also generate significant positive spillovers, in particular by spurring high-quality scientific entrepreneurship.[4]

The way forward, however, probably involves improving the efficiency of the existing division of innovative labor, because large corporate labs are unlikely to regain the importance they once enjoyed. Research in corporations is difficult to manage profitably. Research projects have long horizons and few intermediate milestones that are meaningful to the non-expert. As a result, research inside companies can only survive if insulated from the short-term performance requirements of business divisions. However, insulating research from the business also has perils. Managers, haunted by the spectre of Xerox PARC and DuPont's "Purity Hall" fear creating research organizations disconnected from the main business of the company. Walking this tightrope has proven to be extremely difficult. Greater product market competition, shorter technology life cycles, and more demanding investors have added to this challenge.[5] Companies have increasingly decided that they can do better by pursuing an incremental innovation strategy and sourcing knowledge from outside, rather than betting on making game-changing discoveries in-house.

Consistent with these ideas, Arora et al. (2018) find that the decline of scientific research in corporate R&D after 1980 was mirrored by a drop in the implied value of scientific capability, as

[4]Many important industrial clusters, including Silicon Valley for semiconductors, Detroit for automobiles, and Akron for tires, arose not so much because of agglomeration externalities, as it is commonly thought, but because of spin-offs from leading firms such as Fairchild (Klepper, 2015). Agrawal et al. (2014) find a large innovation premium in regions where small patenting entities coexist with at least one large patenting entity.

[5]Impatient, short-term oriented investors are a familiar and easy target. But even Google, whose management are largely insulated from public investor pressure, has struggled to find an organizational model for managing internal research. Google X, its research arm, currently requires researchers to leave after two years, implying that projects with longer horizons may not be pursued.

measured by stock market valuation and acquisition price. As they also stress, whereas the private value of investing scientific research in-house declined, there is no evidence that the social value of science has declined. Patents continue to build upon scientific knowledge (as measured by citations) and, if anything, the relevant science is more likely to be new rather than old science. In other words, not only is science relevant for invention, but advances in science continue to be useful. This is especially true of corporate research.

The remainder of this chapter is organized as follows. Section 2 describes the rise of the U.S. scientific-industrial complex. Section 3 explains how this ecosystem subsequently changed. Our discussion builds on accounts by Mowery (2009); Mowery and Rosenberg (1998) and others. These authors note that, while in the late nineteenth and early twentieth centuries independent inventors were the primary source of American inventions, the locus of innovation shifted during the interwar years from small firms to large corporations and their labs. By the 1980s, however, small firms (often founded by university scientists) regained their advantage. Interestingly, this rise and fall of the large corporate lab matches quite well the rise and fall of American productivity. Section 4, therefore, explores the idea that corporate labs may be an important engine of economic growth, even when research produced by universities is at a record high.

2 The old innovative ecosystem: 1900-1980

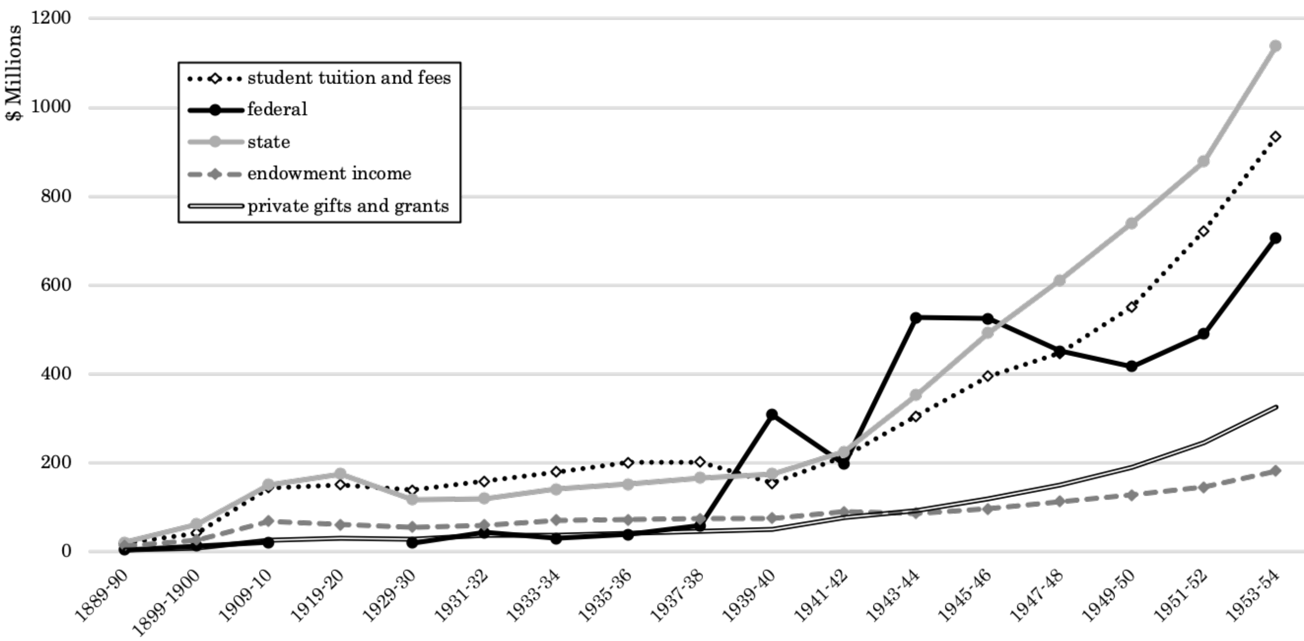
From the early years of the twentieth century up to the early 1980s, large corporate labs such as AT&T's Bell Labs, Xerox's Palo Alto Research Center, IBM's Watson Labs, and DuPont's Purity Hall were responsible for some of the most consequential inventions of the century such as the transistor, cellular communication, graphical user interface, optical fibers, and a host of synthetic materials such as nylon, neoprene, and cellophane. We trace the origins of this system to the fledgling state of American universities in the late nineteenth century, which required existing firms to shoulder the burden of research in order to stay competitive in a technological environment filled with revolutionary advances in the physical sciences. As the interwar period drew to a close, universities began to receive greater support from the federal government. Eventually, universities overtook the corporate sector as a performer of research. For a time, the growth of university research complemented corporate research, principally by providing trained researchers, as well as scientific advances. However, university based research moved from mission-oriented industrial problem solving to curiosity-driven discipline building over the latter half of the twentieth century.

2.1 The rise of research universities

Up until the late nineteenth century, American academia was considered backward. The main application of scientific knowledge was in agriculture, and the pursuit of more abstract natural phenomena were limited. For instance, the American Academy of Arts and Sciences had stated in 1780 that it was devoted to "improvements in agriculture, arts, manufactures, and commerce" (Reich, 1985, p.14). Even the Smithsonian Institutions did not pursue or support basic scientific research during this era (Shils, 1979, p.22). The Land Grant Institutions established after the Morril Act of 1862 were intended to research in "agriculture and [the] mechanic arts," which did not include physics or chemistry. By 1897, a mere 56 PhDs had been earned by Americans in mathematics, 73 in physics, and 101 in chemistry. Full-time research jobs were rare and US-based authors had seldom published in major international journals: only 39 papers in mathematics, 154 in physics, and 134 in chemistry (Kevles, 1979, p.170).

As shown in figure 3, universities in this era relied heavily on state and industry funding, rather than federal funding (Geiger, 2004; Bruce, 1987). According to the Biennial Survey of Education compiled by the Department of Education, the share of federal funding as a source of university revenue had hovered around 4-7% between 1909 and 1939. The share of state funding, on the other hand, was somewhere between 20-30% in the same period (Snyder, 1993). As a result, colleges developed specialties specific to industrial activity relevant to their location. The University of Oklahoma, for instance, pioneered innovations in petroleum engineering such as reflection seismology. The University of Akron and the University of Cincinnati respectively trained specialists that could be employed by the local rubber and tanning industry (Mowery and Rosenberg, 1991). Federal institutions paid very little attention to the pursuit of fundamental knowledge — most federal research was conducted through agencies with clear short-term objectives such as the Coastal, Geological Surveys and the Permanent Commission of the Navy Department (Shils, 1979). These form the origins of the mission-oriented tradition in US universities.

Figure 3: Sources of University Revenue in the United States (1889-1954)



Notes: This graph plots the sources of revenue for the institutions of higher education in the United States. Data is sourced from Snyder (1993), Table 33 and is based on the U.S. Department of Education's Annual Report of the Commissioner; Biennial Survey of Education in the United States. The figure for federal funding sources in 1919-20 is included under state government funding for those years.

The alternative view of the university as a fundamental research institution driven by intellectual curiosity had been pioneered by Alexander von Humboldt, who founded Humboldt University of Berlin in 1809 (Atkinson and Blanpied, 2008). American returnees from these German universities such as Evan Pugh and Samuel Johnson advocated for fundamental research at universities (Shils, 1979). The subsequent establishment of research universities such as Johns Hopkins (1876), Clark (1887) and the University of Chicago (1892) made possible the recruitment of prominent mathematicians such as James Sylvester, who founded the *American Journal of Mathematics* in 1878, and chemists, such as Ira Remsen, who founded the *American Chemical Journal* in 1879 (Kevles, 1979). These early successes spurred established schools to follow suit, with Harvard opening the Jefferson Physical Laboratory in 1884. German-trained physicists and chemists such as Henry Rowland (at Berlin under Hermann von Helmholtz) and Arthur Noyes (at Leipzig under Wilhelm Ostwald) took up prominent positions at Johns Hopkins and MIT respectively, and diffused the norm of curiosity-driven science (Reich, 1985). Rowland, for instance, authored the *Plea for Pure Science* in 1883 for the AAAS address that year, in which he demanded "what must be done to create a science of physics in this country, rather than to call telegraphs, electric lights, and such conveniences by the name of science?" (Rowland, 1883). In the view of Rowland and other like-minded scientists, applied science "drives out" basic (Bush, 1945), making it imperative for universities to defend the latter type. Federal reforms such as the Hatch Act of 1887 and the Adams Act of 1907 allowed federal funds to reach original research that was not immediately applied. Between 1870 and 1893, 39 articles by Americans had appeared in mathematics publications, 144 in physics publications, and 134 in chemistry publications. Between 1894 and 1915, those numbers rose to 372, 303, and 403, respectively.

There is evidence of an increase in quality as well as quantity. Over the same period, the number of papers by American scientists published in prestigious foreign journals such as *Nature* and *Comptes Rendus* (the proceedings of the French Academy) doubled for physics and chemistry and jumped almost eightfold for mathematics (from 39 to 303). The total number of doctorates in these three disciplines also increased from 230 to 820. Perhaps most tellingly, the number of doctoral students in the sciences studying abroad decreased from 189 to 90 (chemistry saw the steepest decline, from 116 to 32). These patterns are consistent with American science catching up to European standards.

As research universities entered the interwar period, the twin norms of mission-orientation and discipline-orientation became a source of increasing tension within, and a demarcator between, these institutions. On the one hand, universities were receiving industrial contracts for research that were focused on specific problems. For instance, the National Rock and Slag Wool Association financed building insulation studies from the University of Minnesota. MIT's electrical engineering department maintained close ties with AT&T from 1902, which supported departmental research and teaching. At MIT, the Research Laboratory of Applied Chemistry (RLAC) led by William Walker aggressively pursued industrial contracts. An endowment fund drive that began at the institute in 1919 resulted in the "Technology Plan," which would secure corporate financing in exchange for tailor-made conferences and access to alumni files for recruitment.[6]

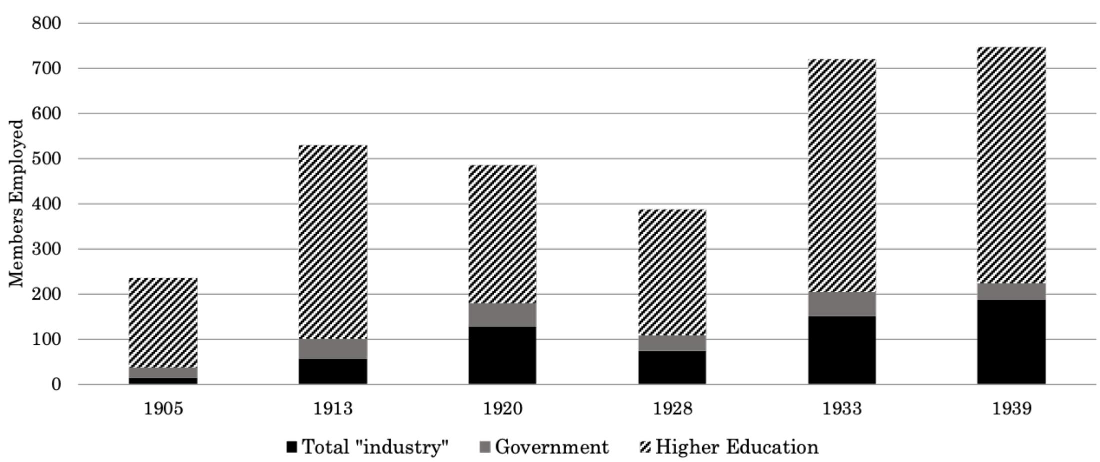
Another incentive for university faculty to collaborate with industry was that many of the exciting research areas required expensive equipment (vacuum tubes, catalysts) often more abundantly found in industrial laboratories. For instance, as the demand from the electrical industry drove MIT to offer its first degree in electrical engineering in 1882 (Reich, 1985, p.24), some of the best aca-

[6]Sponsored industrial research exceeded $100k in 1920-21 and rose to over $270k by 1930 (Geiger, 1986, p.179)

demic researchers at the time, such as MIT's Willis Whitney and William Coolidge, went to General Electric to continue their research. William Carothers, the inventor of nylon, was drawn away from his position at Harvard to DuPont, which could offer him more time for research and greater experimental resources. Synthesizing complex polymers required expensive instruments, such as the molecular still which eliminates excess water in chemical reactions. Large companies helped found many scientific associations; for example, the *Optical Society of America* was founded in 1916 by a group at Eastman Kodak while the *Acoustical Society of America* was founded in 1928 at Bell Labs (Weart, 1979, p.321).

Research universities in this era therefore seem to have become not only more able but also more willing to provide inputs to corporate inventions. Indeed, the employment characteristics of American Physical Society members in figure 4 shows that compared to 1905, the share of physicists working in industry and government had increased to around 10% in the 1930s. Moreover, National Research Council data on scientific employment figures show that scientists and engineers employed in manufacturing industries grew more than sixteen-fold from 2,775 to 45,941 from 1921 to 1946 (Mowery and Rosenberg, 1999).

Figure 4: Employment of American Physical Society Members



Notes: This figure is based on data on the employment affiliations of members of the American Physics Society from Weart (1979), and plots the annual employment share of each destination sector.

However, this pattern of willing university research for industry faced a backlash from within. Prominent departures followed. Chemist G.N. Lewis left MIT for Berkeley citing "industrial intrusions into university research" as a reason. Arthur Noyes (former acting president of MIT and NRC member) also departed from MIT for Caltech after a dispute with Walker as to the future direction of research. MIT's replacement of Richard MacLaurin with physicist Karl Compton from Princeton, and the subsequent shutdown of individual industrial research programs, shows universities defending their institutional logic as builders of scientific disciplines. The operation of the newly founded California Institute of Technology epitomizes this "correction." Advocacy by scientists such as George Hale, lead Caltech to shun direct consultancies with firms, and to only accept "fluid" grants from foundations and firms that could be used for general research. A stark demonstration of universities' willingness to avoid mission-oriented research tasks comes from the closure of flagship government laboratories after World War II. For instance, Harvard informed the Navy in 1944 that it did not wish to house an underwater sound lab. Chicago similarly wished to withdraw from managing the Metallurgical Lab, which designed an experimental reactor for plutonium production (Geiger, 1986, p.32). It was largely due to lobbying efforts by lab management and funding by federal agencies that Caltech's Jet Propulsion Laboratory or Applied Physics Lab were able to persist.

The war-years saw large increases in Federal R&D expenditures rising from \$83.2 million in 1940 to a peak of \$1,313.6 million in 1945 (Mowery and Rosenberg, 1999, p.28). Figure 3 also shows that beginning from 1940, the university sector has been an important beneficiary of this spending increase. Synthetic rubber, mass-produced penicillin, radar , and the atomic bomb demonstrated to policy makers the possible returns that federal investment in science could yield. Universities functioned as hosts of such research efforts. For example, before being moved to Los Alamos, the principal scientific work for the Manhattan project was conducted by academics such as Ernest Lawrence and Robert Oppenheimer at Berkeley, Harold Urey at Columbia, and A.H. Compton at Chicago Metallurgical lab. Cyclotron experiments were run at Minnesota, Wisconsin, Harvard, and Cornell. The Radiation Lab, which studied improvements in radar technology vital to the Allied war effort in the Battle of Britain, had been located at MIT (Geiger, 1993, p.27-9).

The onset of the Cold War and the "Sputnik Shock" gave further justification for federal academic support. Starting with the founding of the Atomic Energy Commission (which largely inherited the infrastructure for the Manhattan Project), wartime projects were re-organized under mission-agencies such as the ONR, NIH and NASA, while the National Science Foundation was established by 1950 to oversee and coordinate these efforts. As a result, federal research dollars for the university sector grew from an estimated level of \$420 million (1982 dollars) in 1935-1936 to more than \$2 billion (1982 dollars) in 1960 and $8.5 billion in 1985. Between 1960 and 1985, the share of university research of GNP grew almost twofold from 0.13 to 0.25 (Mowery and Rosenberg, 1993, p.47). This injection of federal support implied that research universities did not need to rely as much on industrial funding. Moreover, much of the investments by the federal government during the postwar years — even those funded by mission-oriented agencies such as the Department of Defense or the Department of Energy — were aimed at building up stocks of human capital, and provided support for faculty-originated research. Thus, federal research support steadily distanced universities from the specific innovation needs of industry.

The evolution of American research universities since the mid-nineteenth century shows a pendulum swing between mission-oriented and discipline-building research goals. While the beginnings of research universities had been to serve practical purposes, the infusion of German-trained expatriates imbued a new goal of pursuing science for its own sake in these institutions. The postwar federal research expansion enabled universities to free themselves of the need for industry support. By the 1960s, faculty at top research universities were largely pursuing agendas of their own without having to coordinate their efforts with industry or government.

2.2 The rise of the corporate lab

American corporate engagement in science began modestly. The leading firms of the 1870s and 1880s largely relied on external inventions; the railroad companies did not invent steam engines or breaking systems, nor did Western Union invent telegraphy. These leading firms did, however, establish their own industrial labs to evaluate the quality of these external inventions and other inputs, to perform materials testing and quality control, and to trouble-shoot production. Corporate attitude towards the organization of science in for-profit corporations was well expressed in 1885 by T. D. Lockwood, head of AT&T's patent department: "I am fully convinced that it has never, is not now, and never will pay commercially, to keep an establishment of professional inventors, or of men whose chief business it is to invent" (Lamoreaux and Sokoloff, 1999).

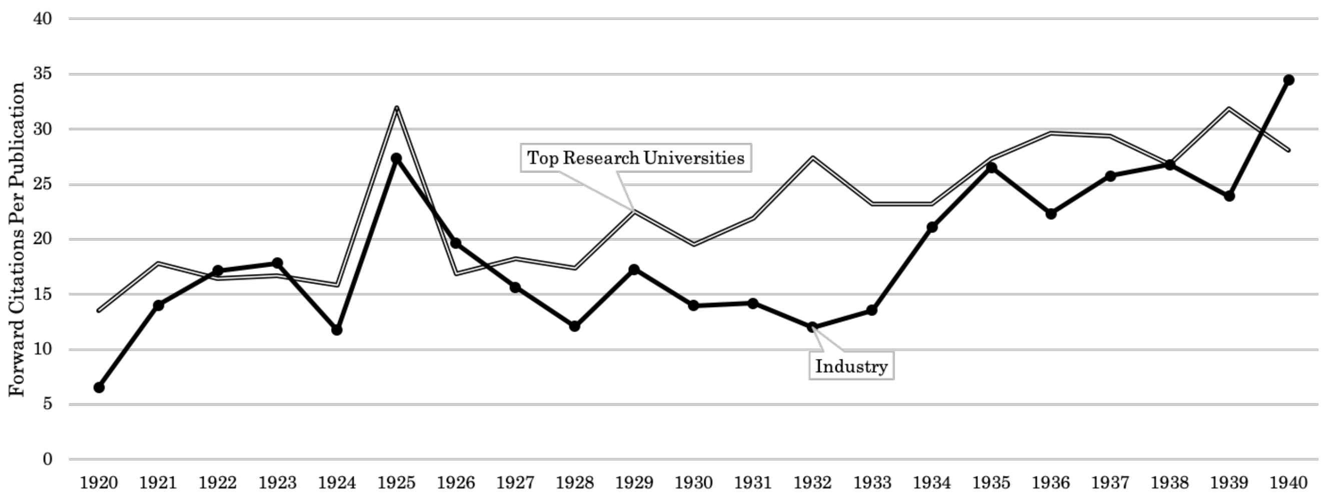
Several pushes and pulls propelled American corporations to create large R&D laboratories. First, there was the German precedent of industrial research in chemical firms that allowed for firms such as BASF, Bayer, and Agfa to thrive in organic synthetic dyes in a highly competitive international market (Reich, 1985, p.41). Second, the strategy of acquiring patents was becoming harder because of rising technical complexity of the traded technologies. For example, DuPont had repeatedly failed in their attempt to use the Bevan, Cross and Topham patents from the United Kingdom to start a viscose rayon process in the United States. It lacked the internal technical and scientific capability to understand these patents and know-how to use them. Eventually, a joint-venture with Britain's Samuel Courtauld & Company (which had the know-how and manufacturing expertise) was necessary to start viscose rayon production in America (Hounshell, 1988). Third, American inventions were challenged by science-based competition across the Atlantic. GE's control over electric lighting in the 1890s, for instance, was solely based on the carbon-filament high-vacuum incandescent variety, first invented by Thomas Edison in 1879. German chemists such as Carl Welsbach and Walther Nernst (the 1920 Nobel Laureate in Chemistry) respectively invented incandescent mantels for gas lamps (a substitute product) and a glower which required no vacuum to operate and was 50% more efficient. Patent rights to the Nernst glower in turn were first sold to the German firm AEG for $1 million and then sold to GE's rival, Westinghouse in 1894 (Wise, 1985). GE management took notice of this "pandora effect" of innovative activity that was difficult to circumscribe and control, and thereby approved electrochemist Charles Steinmetz's proposal to establish the GE Research Laboratory in 1900. The payoffs were evident: William Coolidge (1906) would develop a method using tungsten instead of carbon filaments to increase bulb life, and Irving Langumir (1913) would invent the inert gas-filled lightbulb to reduce blackening, which became the industry standard. The result was a sustained growth in corporate research. The chemical industry, perhaps the most scientifically grounded industry of the first half of the twentieth century, already employed 2,775 scientists in corporate labs in 1921, but grew to 10,918 in 1933 and to almost 45,941 in by the end of World War II (Mowery and Rosenberg, 1999).

Later, the wartime experiences of being part of the National Research Council cemented the faith of prospective lab managers that science could be effectively put to practical applications (Geiger, 2004). The mass production of penicillin, radars using magnetrons, nuclear fission, synthetic rubber were but a few concrete examples of the usefulness of science. This process gained momentum as corporations grew larger and more keen to "routinize" innovation; that is, to originate and manage it instead of relying on an uncertain supply of external inventions (Maclaurin, 1953). Stronger antitrust enforcement also convinced managers buying other firms would be a costlier way to grow than by introducing new products derived from in-house research. At the peak of the corporate lab era in the 1950s, firms such as AT&T, DuPont, IBM, and Xerox employed tens of thousands of scientists whose chief objective was to conduct research to support the companies' existing products and to develop products that would open up new markets.

It is important to emphasize that the science conducted even within the most university-like corporate labs were still aimed at some form of economic problem solving, and hence fell under the category of "mission-oriented" research. Steinmetz's innovations in complex math, for instance, were motivated by the need to better control alternating electric currents (Kline, 1992). Of course, the mission-orientedness of industrial research does not detract from its scientific sophistication (Stokes, 2011). On the contrary, mission oriented research in the invention of the transistor, for instance, could not have been substituted by the more curiosity-driven research by academics. Indeed, even at the early stages of industrial research, Steinmetz had earned himself the presidency of the American Institute of Electrical Engineers, while Langumir had collected his Nobel prize in Chemistry in 1932 for work done at GERL. AT&T Bell Labs president Frank Jewett was instrumental in persuading Compton to take up his presidency at MIT, and later served as president of the National Academy of Sciences from 1939 to 1947. The scientific "merit" of corporate publications measured by forward citations by scientific peers has kept up with (and at times exceeded) research at top universities, as seen in figure 5.

This extensive investment in science enabled firms to exchange personnel and ideas with the university sector in the post war growth era. The evolution of laser technology demonstrates the importance of research sector diversity in producing path-breaking inventions. The main theoretical work leading up to the laser was co-authored by a university scientist (Columbia's Charles Townes) and a corporate researcher (Bell Lab's Arthur Schawlow) (Schawlow and Townes, 1958). The ammonium gas maser, invented by Charles Townes at Columbia's Radiation Lab in 1953, was part of a natural progression in academia toward higher frequencies, from radio to microwave to infrared and visible light. But the private sector also saw the potential in achieving stimulated photonic emission at the visible light range — AT&T and RCA, for instance, recognized that the information content of visible light was far richer than in the microwave range (Gertner, 2013; Hecht, 1992). Universi-

Figure 5: Scientific Citations per Publication, by Sector (1920-1940)



*Notes:*The lines graph the number of forward scientific citations per publications in Web of Science, by sector. "Top Research Universities" refer (in alphabetic order) to UC Berkeley, Brown, Bryn Mawr, Caltech, Chicago, Clark, Columbia, Cornell, Harvard, Hopkins, Illinois, Iowa, Lafayette, MIT, Michigan, Minnesota, Missouri, Nebraska, North Carolina, NYU, Penn, Princeton, Stanford, Wisconsin, and Yale. The "Corporate" sector includes parents and subsidiaries of 200 large industrial firms included in Kandel et al. (2018). We fuzzy-match these university and firm names to the address column of Web of Science publications and count the number of forward scientific citations these publications receive until 2016.

ties, on the other hand, were slower to follow up on the "maser paper" by Schawlow and Townes. Many university scientists such as Gordon Gould (who drafted the "laser memo" at Columbia) left academia to join firms such as Technical Research Group (TRG). With both significant defense and civilian funding available, lucrative positions were available at AT&T, Hughes Aircraft, TRG, IBM, and the American Optical Company. This personnel exchange manifested in active scientific publication activities by industry in this area. A bibliometric analysis of peer-reviewed scientific journals in *Physics Abstracts* for 1963 revealed that 71% of American-authored papers on lasers were written by industrial scientists (Bromberg, 1991, p.98). Complementary engineering skills such as semiconductor doping, vacuum chamber construction, and crystal pulling involved a substantial amount of tacit knowledge. Therefore, firms with the structures for preserving and passing on such knowledge contributed to subsequent breakthroughs. For example, although the IBM group was a latecomer to laser development, their accumulation of knowledge and know-how over the years would yield the invention of dye lasers and semiconductor lasers in the 1960s, a crucial step in miniaturizing laser devices and used today in fiber optic datalinks (Guenther et al., 1991).

In summary, the innovation ecosystem that emerged after WWI saw the emergence and growth of a research university sector, which was maintained at first by industry funds and later through the infusion of postwar federal funding. Throughout this period, corporate labs maintained high-caliber scientific personnel and made complementary investments in instrumentation and experimental equipment. This helped firms to readily absorb the newest scientific developments and accommodate university scientists in their labs. Yet, as research universities continued to expand, the outside options of researchers improved. Corporate labs were forced to give ground to the demands from within their ranks for more space for curiosity-driven research and scientific publication. Overtime, the science science was disconnected from its immediate applications for sponsoring firms. These changes made it increasingly difficult to manage science inside for-profit corporations, leading to a drastic transformation of the American innovation ecosystem beginning in the last quarter of the twentieth century.

3 The "new" innovation ecosystem: 1980-2016

The new innovation ecosystem is characterized by a deepening division of innovative labor between universities and corporations, with the former focusing on research and the latter dedicating their efforts to development. Freed from specific objectives, individual scientists subdivided practical problems, with the subproblems more amenable to scientific investigation. From an industry perspective, however, using the output of university scientists still requires significant coordination and integration. The task of converting scientific insights into inventions that would be the basis of new products and processes became a specialized one. Universities were not well placed to "translate" research findings into executable solutions. Corporations, especially those which lacked internal labs familiar with such mission-oriented research, too found it difficult. Thus, although specialization has had its benefits, the separation between upstream research and downstream applications has also presented formidable challenges.

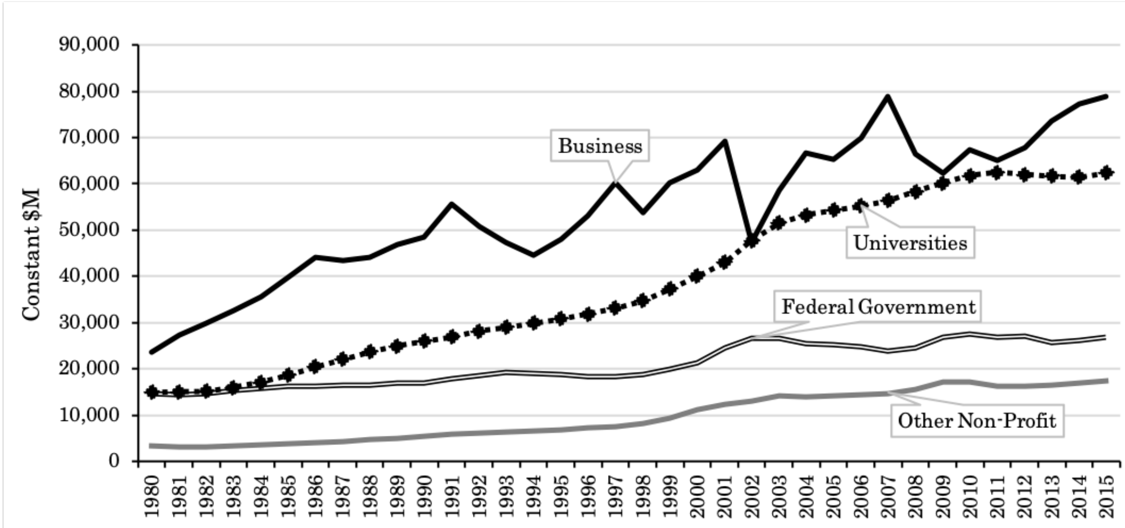
3.1 Universities, the division of innovative labor and the market for technology

University research quality after postwar federal funding increases had accumulated steadily. Academic institutions spent $61 billion on basic and applied research in 2015. University share of total research in 1985 was 23.8% and has risen to 33.6% in 2015 (Boroush, 2017). In the same period, the university share in applied research has almost doubled from 10.0% to 19.8%, while their share of basic research has held at around half of total for the same period.

Universities participate in the division of innovative labor by producing insights into the natural world, as well by directly producing inventions to be developed. In support of such a division of labor, the U.S. Congress passed the National Cooperative Research Act in 1984, which softened the risk of antitrust prosecution by the Department of Justice for firms engaging in R&D collaborations. Perhaps the most widely commented on reform of this era is the Bayh-Dole Patent and Trademark Amendments Act of 1980, which allowed the results of federally funded university research to be owned and exclusively licensed by universities. Since the postwar period, the federal government had been funding more than half of all research conducted in universities and owned the rights to the fruits of such research, totaling in 28,000 patents (Markel, 2013). However, only a few of these inventions would actually make it into the market. Bayh-Dole was meant to induce industry to develop these underutilized resources by transferring property rights to the universities, which were now able to independently license at the going market rate. Licensing, joint ventures, or spinoffs from university research, of course, were not new. As early as 1934, Arnold Beckman, a physical chemist at Caltech, spun off his pH meter invention into what would become National Technical Laboratories (now Beckman Coulter) – the nation's foremost scientific instrument manufacturer. What was new with this reform was that the uncertainty related to licensing federally funded research was now significantly reduced, especially with the diffusion of Technology Licensing Offices (TLOs) in universities.

The share of universities in patenting activity has increased from 1% of total patents in 1975 to 2.5% in 1990. The ratio of patents to R&D spending almost doubled during this period, from 57 to 96 patents per $1 billion. What is remarkable is that the rest of the economy saw a decrease, from 780 to 429 patents per $1 billion of R&D spending (Henderson et al., 1998). Taking a longer view at the number of patents granted shows an even starker contrast: 380 patents were awarded in 1980, while 3,088 were awarded in 2009 (Markel, 2013). The increases in university patent applications and gross licensing income represented in figure 7 underlines this upward trend. University scientists have found it increasingly attractive to start their own businesses, with high-powered incentives and nimble ways that are difficult to replicate in large, established firms. Changes in the institutional

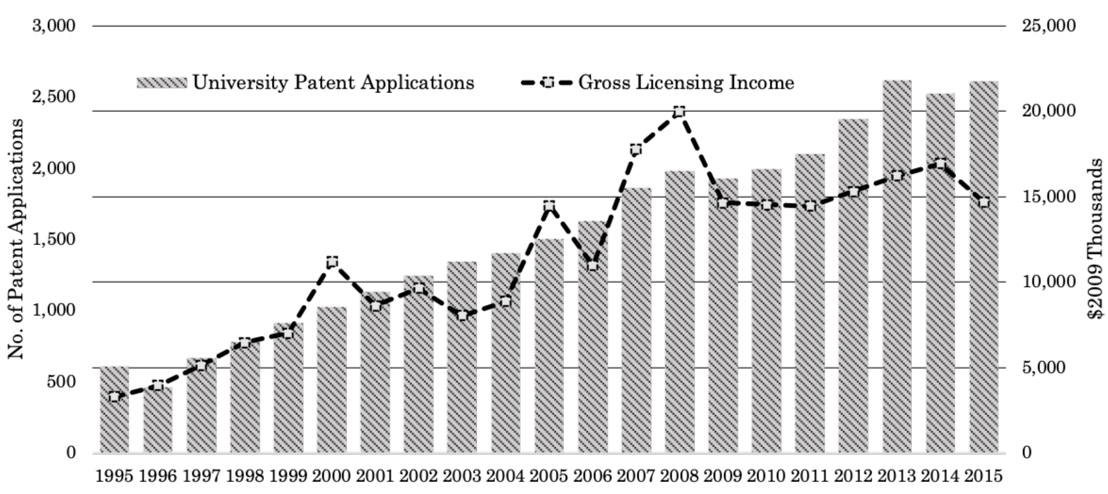
Figure 6: U.S. Applied & Basic Research Expenditure by Performing Sector



Notes: This figure plots the aggregated annual basic and applied research expenditures by performing sector from the *NSF National Patterns of R&D Resources (2014-15)* tables 3 and 4. Figures are adjusted to 2016 dollars using GDP deflator from the World Bank National Accounts dataset.

and legal environments have complemented these trends. Start-ups can get financing from venture capitalists and from SBIR and other government programs (Lerner, 2000; Mazzucato, 2015). Indeed, many firms have been spun-off from non-profit research institutions bringing forth such innovations as the MRI, recombinant hepatitis B vaccine, atomic-force microscope and the Google pagerank algorithm.

Figure 7: Patent Applications and Gross Licensing Income by Universities (1995-2015)



Notes: This plot graphs university participation in technology markets using surey data from the Association of University Technology Managers (AUTM). The line graphs the number of patent applications filed by universities. The bar graphs gross licensing income received by universities. Units are in thousands of 2009 dollars (deflated using GDP figures from Bureau of Economic Analysis, National Economic Accounts, Gross Domestic Product, http://www.bea.gov/national/)

Normative changes on whether university research *should* be used as economic inputs were also important in determining their participation in markets for technology (MFT). Geiger (1993) argues that the student protests of 1968 engendered a general antipathy toward "programmatic" or mission-oriented research. National reports published during the 1970s urged universities to emphasize their teaching functions and contributions to society at large. The normative aversion toward commercial engagements with firms can be gleaned from the public attitude of universities toward collaborations with industry. For instance, Monsanto's $23 million, 12-year research deal with Harvard university in 1974 was kept private until press attention forced it to reveal the terms of its agreement. NIH investigations and hearings at the House Science and Technology Committee also followed similar deals between Hoechst and Massachusetts General Hospital's new genetics department (also affiliated Harvard University) in 1981.[7]

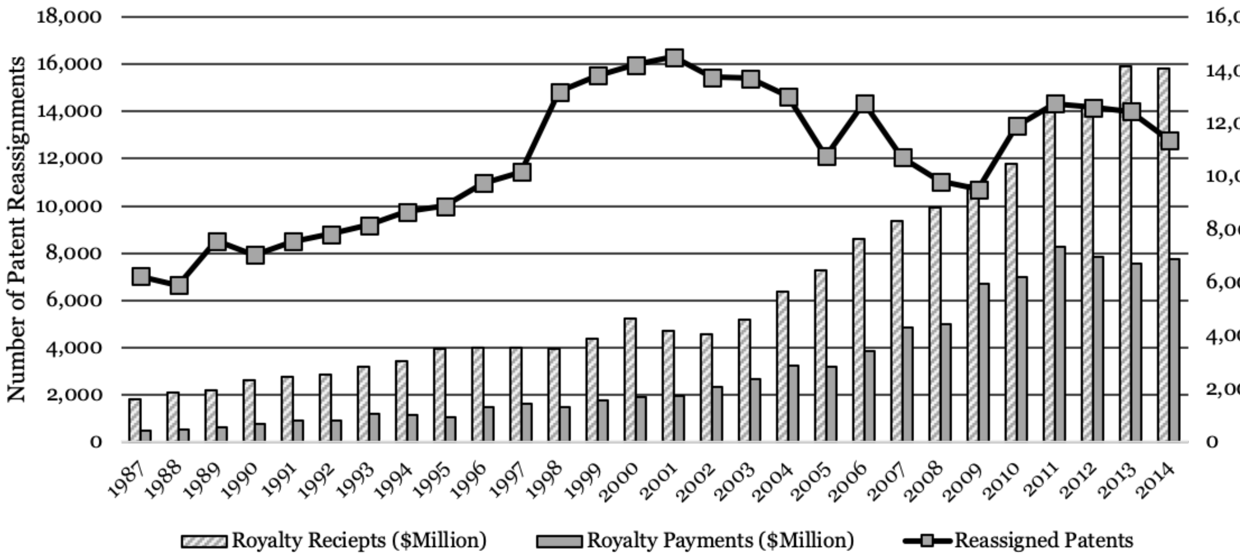
Gradually, however, the need and utility of use-inspired research via industry collaborations were rediscovered due to several factors. First, major government initiatives such as the "War on Cancer" (The National Cancer Act of 1971) focused the need for practical results delivered through scientific research. In support of finding practical applications from basic science, the NSF also created the program on Research Applied to National Needs (RANN). Second, stagnant growth in the 1970s combined with competitive threats from resurgent West German and Japanese manufacturing firms may have made it more permissible for the fruits of academic research to be used as inputs for economic growth. Specifically, state governments in Georgia and North Carolina looked to universities for regional economic development by inducing co-location of research contracting firms and later through spin-offs based on technology developed in academia (Geiger, 2004).

3.2 The expansion of markets for technology and smaller firms

Following Arora et al. (2004, p.6), We define markets for technology (MFT) to include "transactions involving full technology packages (patents and other intellectual property and know-how) and patent licensing." We also include "transactions involving knowledge that is not patented and perhaps not even patentable (e.g., software, or many nonpatented designs) but excluding standard software site licenses." A key characteristic of the new innovation ecosystem is the emergence of small, specialized research organizations that trade *ex ante* (research and consulting projects) and *ex post* (patents,

[7]Source: https://www.thecrimson.com/article/1981/7/3/biotechnology-and-the-faustian-dilemma-pscientists/

Figure 8: Patent Reassignments (USPTO) and International licensing royalties for industrial processes (BEA)



Notes: Patent reassignment data is from the USPTO Patent Assignment Database (2018). M&As, security interests, name changes, errors, and employer to employee assignments are censored out. Details on cleaning method can be found in (Serrano, 2010; Ma et al., 2017). Royalty receipts measure income generated by U.S. businesses by sales of industrial processes to non-affiliates abroad. Royalty payments measure the same for purchase of such processes from non-affiliates abroad. Data is sourced from the BEA's Surveys of Current Business and International Services Tables from the BEA website: https://apps.bea.gov/iTable/index$_ita.cfm$

software licenses, chip designs) knowledge products. These smaller firms either directly commercialize their ideas by introducing new products to the market or sell them on to larger firms with downstream capabilities, in sharp contrast to the earlier system, where large firms originated their own inventions.[8]

While venture capital-backed startup firms have been around since the 1950s (for instance in the laser industry for defense contracts), their rise in the American innovation ecosystem occurred only after the emergence of the semiconductor and biotechnology industries. Indeed, Mowery and Rosenberg emphasize that while large firms such as IBM and AT&T were responsible for devising more general purpose hardware such as the IBM 360 and the transistor, antitrust pressures from the Department of Justice (e.g. the 1956 settlement between the DOJ and AT&T) made it very difficult for them to enter downstream markets using that technology. Aided by liberal licensing policies that resulted from this pressure, small follow-on firms such as Microsoft, Apple, Texas Instruments and Fairchild Semiconductors could rapidly develop improved iterations of the original product (Malerba,

[8]To be clear, the era preceding our "old" innovation ecosystem had prominently featured individual inventors who made their living by selling patent rights such as Charles Goodyear (vulcanized rubber patent in 1844) and Henry Bessemer (Bessemer process patent in 1855). Research consulting activities were contracted by the petroleum and telegraph sectors: Standard Oil employed Herman Frasch to lower the sulfur content of its newly opened Ohio fields in the 1880s; Western Union employed Thomas Edison for various technical solutions since the 1870s (Birr, 1979).

1985; Tilton, 1971). For instance, Flamm (1988) counts at least 80 computer start-ups in the mid-1950s that were catering for defense contracts and later consolidated and re-purposed for civilian use. The role of firms such as Genentech, which successfully commercialized a university research-born invention into mass produced human insulin, has been crucial in encouraging entry by private equity firms into the biotechnology sector which lent capital to scientist inventors that specialized in monoclonal antibodies and DNA splicing (Pisano, 2006).

Intellectual property rights have been significantly strengthened, first in the United States and subsequently in other countries (Guellec and de La Potterie, 2007; Jaffe and Lerner, 2006). At the national level, the Federal Courts Improvement Act of 1982 established the U.S. Court of Appeals for the Federal Circuit, streamlining judgment on patent-related cases. Select sectors have also received added attention: the Semiconductor Chip Protection Act of 1984 for instance strengthened IP protection for chip designs. Also, while software was unanimously ruled by the Supreme Court as unpatentable in 1972, successive cases since then have reopened aspects of the Court's decision and allowed for hardware embodying software and software embodying business processes to be patented (Arora et al., 2004, p.61). Globally, the office of the U.S. Trade Representative has consistently pushed for stronger enforcement of intellectual property rights, and was integral in inserting the Agreement on Trade-Related Aspects of Intellectual Property Rights (TRIPS) agreement into the Uruguay Round of 1995. Also, in spite of being far from a perfect market (Gans and Stern, 2010), the diffusion of online platforms and intermediaries continue to reduce the friction involved in trading patents.

As a result, American corporations reported $92 billion of income from licensing intellectual property in 2002, and the supporting IRS data show an annual growth of 11% from 1994 to 2004, which outpaced average GDP growth (3.42%) in the same period (Robbins, 2009). Figure 8 shows that the number of transferred patents as measured by reassignments has also risen substantially from around 7,000 to over 12,000 cases per year between 1987 and 2014.[9] Moreover, business models specializing in selling intellectual property without engaging in downstream manufacturing and sales have been validated by firms such as Exponent (chemicals), Genentech (biotech), and ARM (fabless semiconductor design). What is significant about the latter two firms is that unlike traditional

[9] Authors' calculations based on data from the USPTO Patent Assignment Dataset (Graham et al., 2018)

research consulting firms such as SRI, which carry out contract research on behalf of clients, they are able to provide technology products in a disembodied form (patents and chip design blueprints).

3.3 The decline of corporate research

A major transformation of the American innovation ecosystem has been the downsizing and decline of corporate labs. The decline in corporate research is especially pronounced given the increase in the average size of America's leading corporations. For example, net turnover for GE and IBM in 1980 hovered around $25 billion and $26 billion respectively in 1980, and grew to $100 billion and $82 billion in 1998. In 1979, GE's corporate research laboratory employed 1,649 doctorates and 15,555 supporting staff, while IBM employed 1,900 staff and 1,300 doctorate holders. The comparable figures in 1998 for GE was 475 PhDs supported by 880 professional staff, and 1,200 doctorate holders for IBM (National Research Council, 1980; 1998). Indeed, firms whose sales grew by 100% or higher between 1980 and 1990 published 20.6 fewer scientific articles per year. This contrast between sales growth and publications drop persists into the next two decades: firms that doubled in sales between 1990 and 2000 published 12.0 fewer articles. Publications dropped by 13.3 for such fast growth firms between 2000 and 2010.[10]

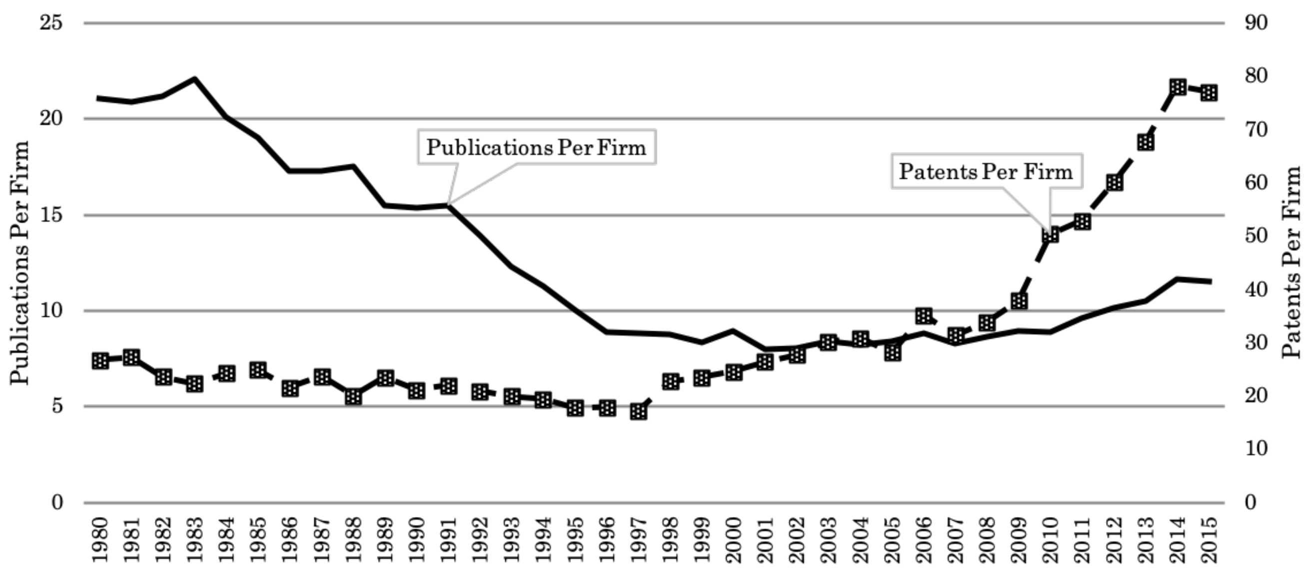
A prominent recent example of corporate withdrawal from science is DuPont's closing of its Central Research & Development lab in 2016. Established in 1903 as the Experimental Station, DuPont Central Research Department was staffed and run on par with top academic chemistry departments. However, in the 1990s, DuPont's attitude toward research changed as the company started emphasizing business potentials of research projects. As a result, the number of first-authored journal articles fell from around 749 to 245 between the years 1994 and 2015, while the number of patents filed with the USPTO increased from around 1,600 in 1994 to close to 3,500 in 2012, reflecting a shift to downstream development activities. Following pressure from activist investor Nelson Peltz, on January 4, 2016, DuPont's research lab ceased to operate as a central research unit.

Aggregated data from NSF shows a similar pattern of corporate research decline, whereby the ratio of basic to applied research in corporate R&D has declined from 50.7% in 1985 to 42.5% in 2015

[10] Calculations based on authors' data on Compustat firms matched to Clarivate Web of Science and EPO Patstat. Details in Arora et al. (2017).

(Boroush, 2017, Tables 3 and 4). Arora et al. (2018) disaggregate this trend further, and find that while a significant fraction of corporate publication decline can be attributed to entry by firms that do not publish or publish very little, even incumbents with established research programs also markedly decreased their research. The decline in publications is most evident in high-quality publications, and the implied value of scientific capability (measured by stock market valuations or by the acquisition price in M&A deals) also declined. By contrast, patenting by large American firms increased, and the implied value of patents, including the premium paid for patents in M&A, did not decrease.

Figure 9: Scientific Publications and Patents by Compustat Firms (excluding life sciences)



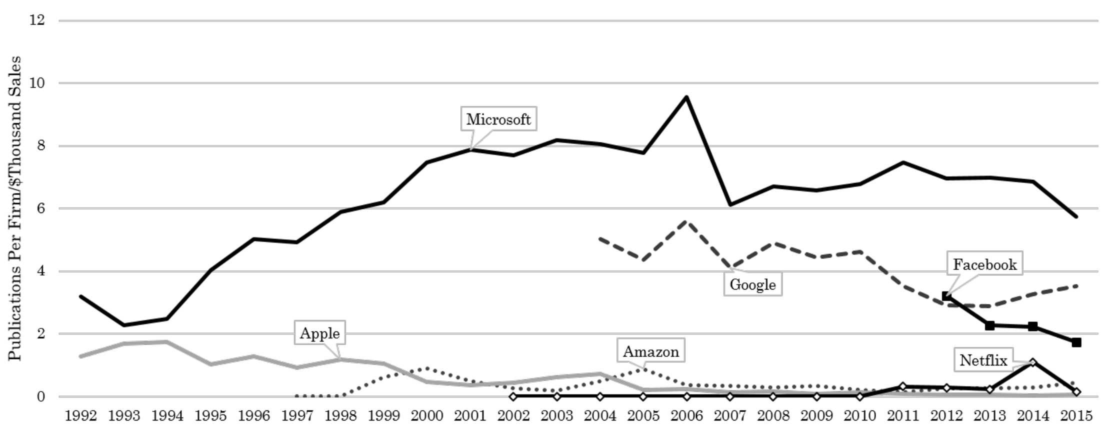
Notes: The solid lines represent the average number of publications in Clarivate Web of Science matched to Compustat firms with over $10 million of R&D Stock and in industry classes excluding the life sciences sector. The broken lines represent the same for patents (details on matching procedure in Arora et al. (2017)).

We use corporate publications data from 1980 to 2015 to explore these trends in more detail. Our sample consists of all R&D performing listed U.S. headquartered firms available in Compustat from 1980 to 2015. We match the names of these firms to the author addresses of scientific articles found in the Clarivate Web of Science's Science Citation Index and Conference Proceedings files. We also match these firm names to the assignee names for U.S. utility patents available from EPO Patstat. Details on the matching process are available from Arora et al. (2017).[11] The results in Arora et al. (2018) are summarized in figure 9, which graphs scientific publications and patents by Compustat firms with at least $10 million of R&D stock. Consistent with their finding, publications by firms approximately halves from around 20 to 10 between 1980 and 2015. In contrast, patenting

[11]We thank Lia Sheer and Honggi Lee for their excellent assistance on constructing the dataset.

by firms increases from around 20 to over 70 patents per year in the same period. Among large U.S. public firms with over $100 million in R&D stock, 183 out of 211 firms (86.7%) published at least one scientific article in 1980. This number dropped to 64.4% in 2015 (444 firms out of 689 published). The decline is more pronounced for the most research active firms: the ratio of firms that publish more than 10 articles per year have dropped from 50.2% (106 out of 211 firms in 1980) to 25.4% (175 out of 689 firms in 2015). The average number of scientific publications per $1 million of R&D spending has also declined from 0.726 between 1980 and 1985 to 0.369 articles between 2010 and 2015. The decline also seems to be more pronounced for older firms. For instance, there were 124 firms out of 182 (68.1%) listed on the stock market on or before 1980 that published in 2015. This ratio rises to 76.7% (23 out of 30) for firms listed in 1995, and 74.3% (29 out of 39) for firms listed in 2000.

Figure 10: Scientific Publications per $Thousand Sales for new IT Sector Firms



Notes: The scientific publications of Apple, Amazon, Facebook, Google, Microsoft, and Netflix matched to the address column of publications in Web of Science are summed each year and divided by the $ thousand sales.

Furthermore, firms in the IT sector do not seem to have bucked the trend of secular decline in corporate science. Figure 10 shows publications per $ thousand sale for Facebook, Amazon, Apple, Google, Microsoft, and Netflix. These firms collectively have replaced the petroleum sector as the largest American firms. Apple, for instance, has become the first firm in U.S. history to exceed a market capitalization of over $1 trillion. It is true that firms in this group tend to publish more than other firms: in 2015, they published on average 148.9 articles, which is around 10 times the average for all firms in that year (15.2 articles). However, there is significant heterogeneity between them: for instance, Google and Microsoft are the dominant contributors to journals, together publishing over 95% of all articles from these six firms. Moreover, save for Microsoft, publications normalized by sales does not seem to exhibit an increasing trend between 1992 and 2015.

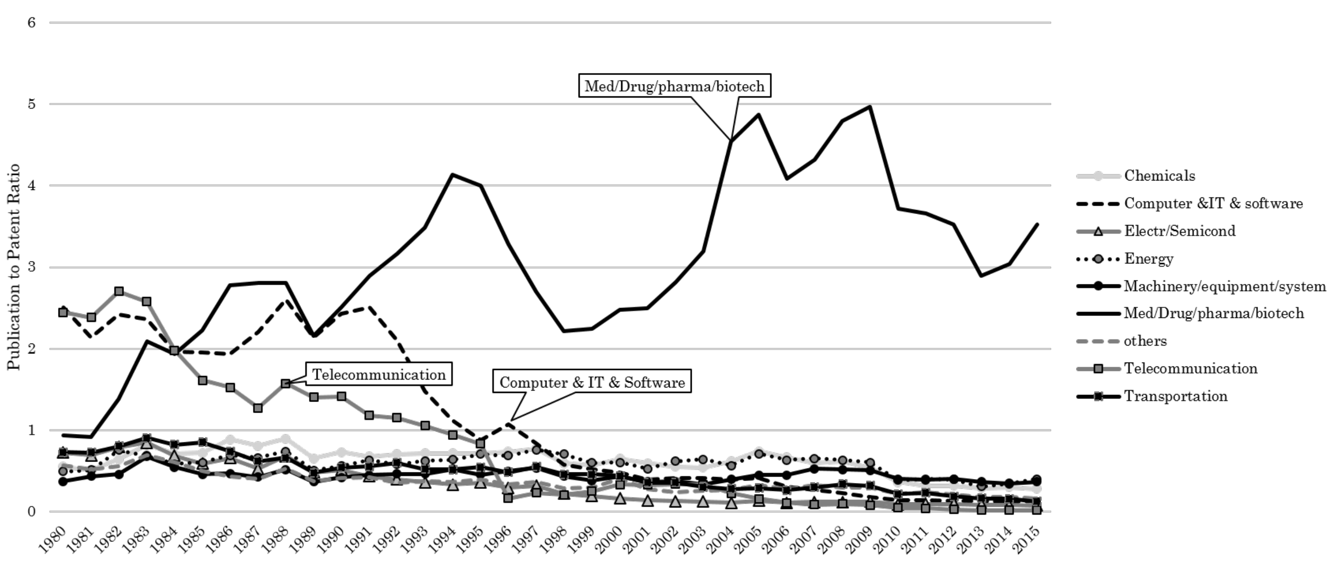
Of the 396 public firms publishing at least one scientific article in 1980, 260 (65.7%) see a drop in publications in 1990. Similarly, 326 out of 498 firms (65.5%) publishing in 1990 see a drop in 2000. The comparable figure for the 2000-2010 period is even higher: 620 out of 849 (73.0%) firms publishing in 2000 report less publications in 2010. To investigate this trend further, Table 1 summarizes publication and patenting trends for the top ten firms that have published the most scientific articles for the 1980s, 1990s, and 2000s. We then observe how the publishing and patenting behavior of these firms change in the succeeding decade. As expected, the firms mentioned in the anecdotes above also show some of the deepest cuts. Table 1's "Top publishers in 1980-99" section indicates that GE on average saw a drop of 219 articles between 1980s and 1990s (from 596 to 377), while articles by Xerox decline from 344 to 240 per year. Also, IBM's stagnation in publications during the 1990s (a 1% decline) contrasts with a near doubling in patenting in the same period and is consistent with qualitative evidence presented by Bhaskarabhatla and Hegde (2014). According to the authors, IBM's pro–patent policies introduced by James McGroddy in 1989 incentivized researchers to patent rather than publish research results (in contrast, IBM practice in most of the 1980s was to discourage patenting). An annual evaluation system for IBM inventors graded them on the number of TDB (Technical Disclosure Bulletin) publications or patents filed. Because TDB publications usually consisted of 2-3 page write-ups of internal lab notes, it has been recounted that inventors preferred to publish rather than patent. This changed as McGroddy's new system required inventors to earn a quarter to a half of all points on patents. Bhaskarabhatla and Hegde (2014) hence find a drop in TDB publications and an increase in patenting by IBM inventors after 1989. The consistent decline in publications that we are seeing throughout our period for IBM therefore are consistent with the change in managerial direction documented by the authors.

Table 1 also shows several anomalies to this overall pattern of decline that deserve mention. First, the absolute number of publications declines sharply (by 81%) at AT&T from the 1990s to the 2000s consistent with the firm's restructuring efforts. However, the same change for publications normalized by annual R&D expenditure is positive. This is because AT&T's R&D budget had shrunken even more drastically, from $4,083 million in 1995 to $640 million in 1996, since it had spun off Bell Labs to Lucent technologies (AT&T's R&D budget has steadily declined from this point and only recovered in the 2010s).

Second, DuPont registers a slight increase in publications between the 1980s and 1990s. However, the growth is only by 9 articles per year and is promptly reversed in the following decade, where there is a drop of 370 articles, from 690 in the 1990s and 320 in the 2000s. The pattern is consistent with the anecdotes that attest to the firm's management aiming to accede to expectations in the capital markets to downsize R&D expenditures in basic science.

Third, firms in the life sciences such as Pharmacia, Lilly, Bristol Myers Squibb, Pfizer, and Amgen have significantly increased publications. In the case of Pfizer and Amgen in the 2000s, the increase is keeping up with changes in R&D expenditures (unlike the AT&T case above). Part of this pattern may be due to consolidation in this sector: for instance, while Pfizer had acquired Wyeth in 2009, scientific publications continued to be attributed to addresses with Wyeth's name. Since we account for such M&A activity using data from SDC Platinum, Bureau Van Dijik's Orbis database, and web searches, increases may be possible after acquisition if the old firm's name is used after the acquisition.

Figure 11: Ratio of Publications per Firm to Patents per Firm, by Industry



Notes: This graph plots the ratio of publications to patents per firm in eight main industrial sectors. The number of publications per firm is calculated by matching publications in Clarivate Web of Science to Compustat firms with over $10 million of R&D Stock. The number of patents per firm is calculated by matching assignee names in EPO Patstat to the same firms (details on the matching process is available in Arora et al. (2017)). Publication to Patent Ratio is calculated by dividing the number of publications per firm by the number of patents per firm.

However, comparisons with other sectors that have had strong merger activity suggests that this

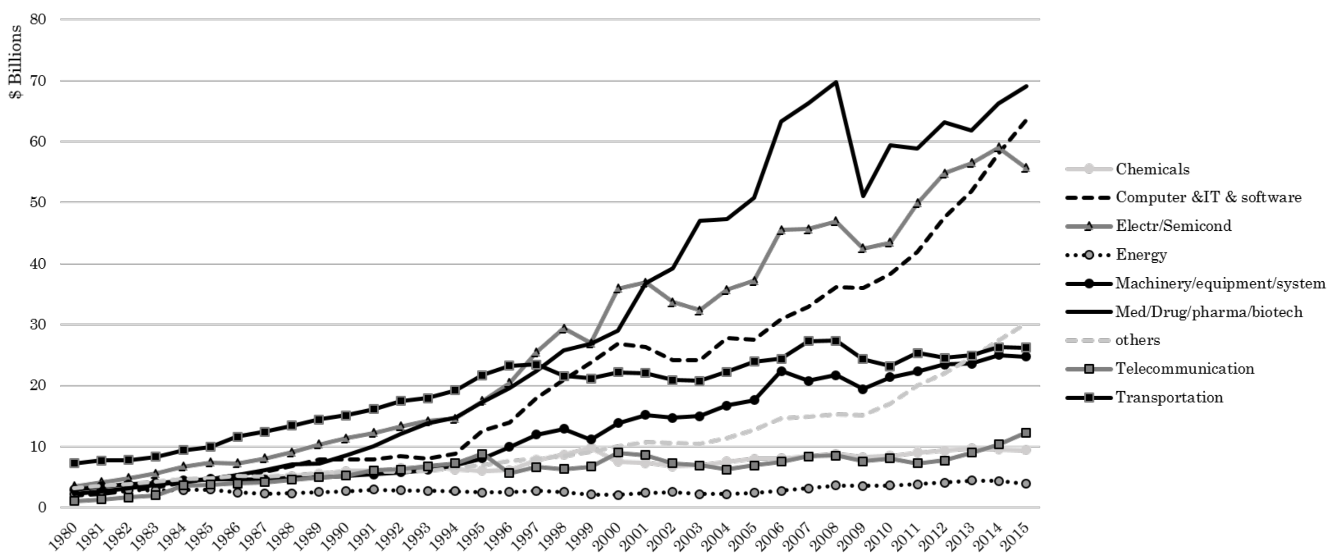
Table 1: Changes in Publications and Patents by top 10 Publishers for each decade from 1980 to 2015

		Publications Per Year				Patents Per Year			
Rank	**Top 10 publishers in 1980-89**	**1980-1989**	**1990-1999**	**% Change**	**% Change (R&D Normalized)**	**1980-1989**	**1990-1999**	**% Change**	**% Change (R&D Normalized)**
1	AT&T CORP	1,889	1,009	-47%	-59%	371	422	14%	-13%
2	INTL BUSINESS MACHINES CORP	1,610	1,596	-1%	-30%	537	1,494	178%	96%
3	DU PONT (E I) DE NEMOURS	600	690	15%	-32%	348	481	38%	-19%
4	GENERAL ELECTRIC CO	596	377	-37%	-54%	889	829	-7%	-32%
5	EXXON MOBIL CORP	514	336	-35%	-30%	249	239	-4%	2%
6	XEROX CORP	344	240	-30%	-55%	228	555	144%	59%
7	PHARMACIA & UPJOHN INC	334	468	40%	-58%	101	49	-52%	-86%
8	CBS CORP -OLD	274	66	-76%	-62%	400	216	-46%	-15%
9	ROCKWELL AUTOMATION	272	127	-53%	-75%	165	117	-29%	-62%
10	LILLY (ELI) & CO	253	469	86%	-39%	89	137	54%	-49%
Rank	**Top 10 publishers in 1990-1999**	**1990-1999**	**2000-2009**	**% Change**	**% Change (R&D Normalized)**	**1990-1999**	**2000-2009**	**% Change**	**% Change (R&D Normalized)**
1	INTL BUSINESS MACHINES CORP	1,596	1,053	-34%	-43%	1,494	3,511	135%	104%
2	LUCENT TECHNOLOGIES INC	1,244	670	-46%	-7%	797	764	-4%	65%
3	AT&T CORP	1,009	192	-81%	53%	422	288	-32%	450%
4	DU PONT (E I) DE NEMOURS	690	320	-54%	-42%	481	338	-30%	-13%
5	BRISTOL-MYERS SQUIBB CO	552	615	11%	-55%	124	157	27%	-49%
6	LILLY (ELI) & CO	469	817	74%	-44%	137	91	-33%	-79%
7	PHARMACIA & UPJOHN INC	468	merged with Pfizer (2003)	N/A	N/A	49	merged with Pfizer (2003)	N/A	N/A
8	ABBOTT LABORATORIES	456	575	26%	-48%	134	101	-24%	-69%
9	PFIZER INC	394	1,489	278%	-30%	101	235	132%	-57%
10	GENERAL ELECTRIC CO	377	534	42%	-22%	829	1,143	38%	-24%
Rank	**Top 10 publishers in 2000-2009**	**2000-2009**	**2010-2016**	**% Change**	**% Change (R&D Normalized)**	**2000-2009**	**2010-2016**	**% Change**	**% Change (R&D Normalized)**
1	PFIZER INC	1,489	2,006	35%	28%	235	145	-38%	-41%
2	INTL BUSINESS MACHINES CORP	1,053	948	-10%	-18%	3,511	6,733	92%	75%
3	LILLY (ELI) & CO	817	788	-3%	-34%	91	59	-36%	-56%
4	JOHNSON & JOHNSON	680	493	-28%	-48%	108	110	2%	-28%
5	LUCENT TECHNOLOGIES INC	670	merged with Alcatel (2006)	N/A	N/A	764	merged with Alcatel (2006)	N/A	N/A
6	BRISTOL-MYERS SQUIBB CO	615	845	37%	-1%	157	169	7%	-22%
7	ABBOTT LABORATORIES	575	489	-15%	-30%	101	377	272%	204%
8	WYETH	548	merged with Pfizer (2009)	N/A	N/A	123	merged with Pfizer (2009)	N/A	N/A
9	GENERAL ELECTRIC CO	534	667	25%	-27%	1,143	1,659	45%	-15%
10	AMGEN INC	528	826	56%	15%	66	97	47%	8%

Notes: This table describes annual patenting and publication activities of Compustat firms that are the top publishers for each decade from 1980 to 2016 (1980-1989, 1990-1999, 2000-2009, 2010-2016). We divide the total number of publications by number of years in every decade for U.S. headquartered firms in Compustat after matching them to the address information in each Web of Science article. After ranking the top 10 publishers each decade by publications per year (first column), we calculate the percentage change between the previous decade and the next decade (fourth column). We also divide the number publications each year by $ million R&D spending and average over each decade for each firm. The percentage differences between each decade in this measure is presented in the sixth column. The same is done for patents from the seventh to tenth columns.

is not simply an artifact of mega mergers between large pharmaceutical firms. Figure 11 plots the ratio between the number of scientific publications per firm and patents per firm by main industrial sector, and indicates life sciences firms have grown this ratio from close to one in the 1980s to between three and five in more recent years. This is in direct contrast to the telecommunications and IT sector, which exhibit a decline in this ratio over the same period (both more than halve their publications to patent ratio). Total R&D expenditure broken down by sector in figure 12 shows that both life sciences and the IT sectors have increased overall expenditure, especially during the 2000s. Hence, it is less likely that the drop in ratio in the publications to patent ratio for the IT sector was due to a decline in R&D expenditure. Rather, it is likely that the composition between "R" and "D" activities have shifted in favor of the latter. Conversely, the rise in publications to patent ratios of life sciences firms would indicate that a similar shift to development activities has not occurred in the life sciences. In future work, firm level microdata from the Census bureau's Business R&D and Innovation Survey (BRDIS) may help us identify more concretely the ratio between "R" and "D" activities by industry.

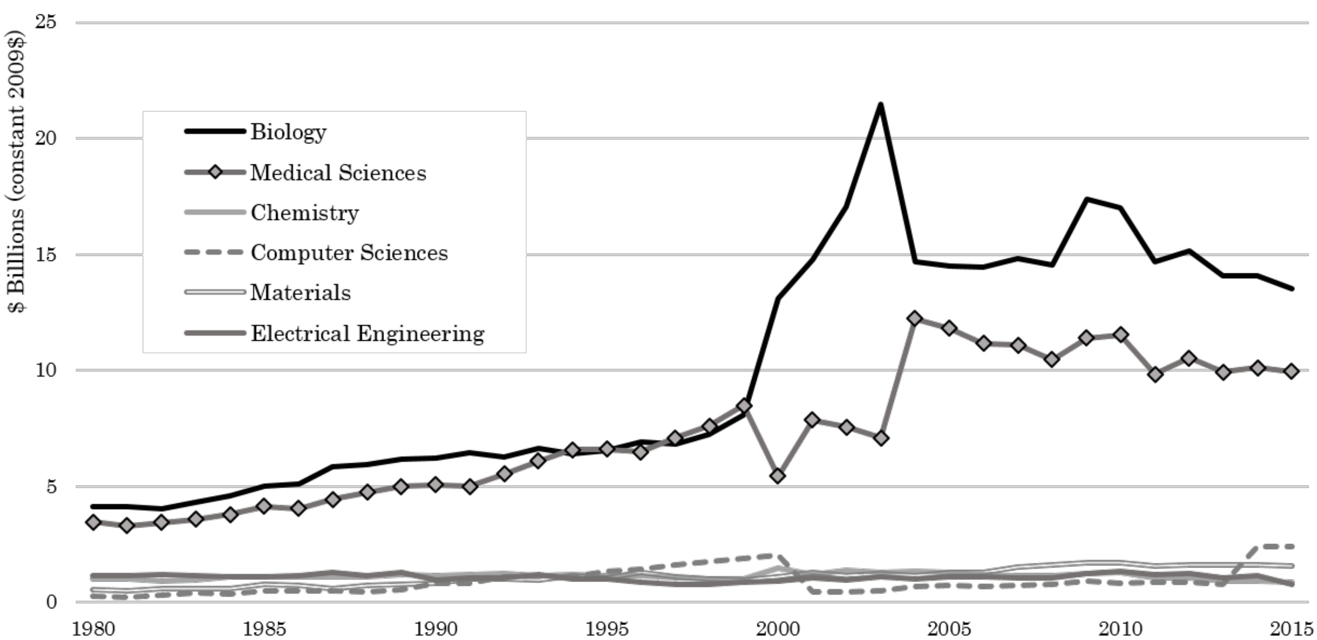
Figure 12: Total Corporate R&D Expenditure, by Industry



Notes: This graph plots the total R&D expenditure in billion dollars in eight main industrial sectors. Firm industry classification is based on the SIC code available in Compustat. We sum R&D expenditure (Compustat mnemonic "XRD") per year per industry.

Apart from an overall rise in sector size, We identify four reasons for the pharmaceutical and biotech sector bucking the overall trend of declining scientific output: first, products in the life sciences generally require regulatory approval, and scientific publications may help build credibility for the product (Penders and Nelis, 2011; Penin, 2007; Simeth and Raffo, 2013). Pharmaceutical products also require the cooperation of physicians who prescribe the products to patients. This implies that drug adoption also depends on convincing these intermediaries of their quality through communication channels such as scientific publications (Azoulay, 2002; Hicks, 1995). Third, larger incumbent firms may wish to pre-empt patenting by smaller upcoming firms by publishing major findings and datasets. For instance, one of the motivations for investment in and publication of the "Merck Gene Index" seems to have been to pre-empt patent filings from biotech startups that such as Incyte pharma and Human Genome Sciences, whose business model built on monetizing Expressed Sequence Tags (EST) in the 1990s (Contreras, 2011).

Figure 13: Federal Obligations by Selected Subfields, FY 1980-FY 2015



Notes: This graph replicates figure 4 on Merrill (2018) using data from the Federal Funds for Research and Development Data series, available from https://www.nsf.gov/statistics/srvyfedfunds/ Biology excludes environmental sciences. Materials includes materials engineering and metallurgy.

Finally, there has been a general increase in federal funding for biomedical research through the NIH, from $2.5 billion in 1980 to $15 billion in 2001 and $29 billion in 2015. Figure 13 shows that this steep increase in federal funding for life sciences has not been matched in other sectors such as chemistry, computer sciences, materials, and electrical engineering. Large-scale federal projects such as the Human Genome project often require disclosure of research results, as in the example of the Bermuda and Fort Lauderdale principles which required genome sequences to be published within 24 hours of sequencing during the Human Genome Project (HGP). These policies would have increased publication output by firms that made use of NIH funds, but also increased output for non-funded firms that could freely access newly available public resources such as genome sequences to increase research productivity. However, this confluence of regulator and competitor incentives and public resources is unique to the life sciences, which may explain why it has stood out among other sectors.

Overall, the new innovation ecosystem exhibits a deepening division of labor between universities that specialize in basic research, small start-ups converting promising new findings into inventions, and larger, more established firms specializing in product development and commercialization (Arora and Gambardella, 1994). Indeed, in a survey of over 6,000 manufacturing- and service-sector firms in the U.S., Arora et al. (2016) find that 49% of the innovating firms between 2007 and 2009 reported that their most important new product originated from an external source. In this view, smaller firms have a comparative advantage in generating inventions, whereas larger firms have an advantage in exploiting them. Large firms would therefore invest in scientific capability not so much to generate knowledge as to be effective buyers of knowledge.

3.4 Why has corporate science declined?

The withdrawal from science by large corporations resulted from a confluence of factors. One reason was that, as competition intensified and the interval between invention and commercialization narrowed, it became increasingly difficult for corporations to profit from their in-house research. As former Bell Labs researcher Andrew Odlyzko (1995, p.4) notes: "xerography was invented by Carlson in 1937, but it was only commercialized by Xerox in 1950. Furthermore, there was so little interest in this technology that during the few years surrounding commercialization, Xerox was able to invent and patent a whole range of related techniques, while there was hardly any activity by other institutions. This enabled Xerox to monopolize the benefits of the new technology for over two decades. [... By contrast,] when Bednorz and Mueller announced their discovery of high-temperature superconductivity at the IBM Zurich lab in 1987, it took only a few weeks for groups at University of Houston, University of Alabama, Bell Labs, and other places to make important further discoveries. Thus even if high-temperature superconductivity had developed into a commercially significant field, IBM would have had to share the financial benefits with others who held patents that would have been crucial to developments of products."

Another factor that may have reduced large firms' ability to profit from their in-house research was the trend toward narrower firm scope. Starting from the 1980s, Wall Street investors increasingly pushed large public firms to "stick to their knitting" and divest unrelated units. However, diversified firms may be precisely the ones best positioned to exploit the unpredictable outcomes of scientific research because, as Richard Nelson (1959, p.302) noted, "[a] broad technological base insures that, whatever direction the path of research may take, the results are likely to be of value to the sponsoring firm." Thus, as firms concentrated on their core markets, their incentives to invest in scientific research may have declined.

Trade, outsourcing, and offshoring of manufacturing may also have reduced the incentives to invest in research. We highlight two possible mechanisms for this negative effect. First, moving manufacturing to locations far from where R&D takes place could reduce interactions between research and production, which may hinder innovation. Second, outsourcing may also undermine in-house research through a dynamic competition effect. Foreign suppliers may begin by manufacturing simple, low-cost components, but over time they tend to move upstream to more complex tasks until the core competencies of the outsourcing firms, such as design and innovation, are under threat. For instance, in the early 1980s, General Electric was still investing heavily in its own manufacturing capability when it decided to outsource the production of some low-end microwave oven models to Samsung, then a little known firm outside of Korea. The initial agreement was for only 15,000 units, but within two years, General Electric had surrendered most of its microwave production capabilities to Samsung. This paved the way for Samsung's rise as a dominant firm, and may well have reduced General Electric's incentives to invest in microwave technology, as well as other areas of technology such as spacecraft communication and radar applications that rely on it.

Large firms also started to invest less in internal research, not only because these investments became less valuable, but also because tapping into external sources of knowledge and invention became increasingly easy. Historically, many large labs were set up partly because antitrust pressures constrained large firms' ability to grow through mergers and acquisitions. In the 1930s, if a leading firm wanted to grow, it needed to develop new markets. With growth through mergers and acquisitions constrained by anti-trust pressures, and with little on offer from universities and independent inventors, often it had no choice but to invest in internal R&D. The more relaxed antitrust environment in the 1980s, however, changed this status quo. Growth through acquisitions became a more viable alternative to internal research, and hence the need to invest in internal research was reduced.

Corporate labs also historically operated in an environment where university research and start-up inventions were scarce. To generate a steady flow of high-quality inventions, large firms had to develop them in-house, typically by setting up a large lab. As discussed above, however, universities and small firms became over time more reliable sources of invention. As the volume of external research increased, corporate labs also found it difficult to keep up with the pace of technological progress. The attractiveness of external technology markets relative to internal research increased.

Finally, legal and technological developments further enhanced the attractiveness of technology markets. Greater protection of intellectual property rights in the 1980s reduced the risk of expropriation in technology transactions. The diffusion of online platforms (e.g., Procter Gamble's Connect + Develop) and the growth of technology market intermediaries (e.g., yet2.com Marketplace, InnoCentive) rendered contracting for innovation easier and less expensive, reducing frictions in technology markets. All these developments made technology markets more attractive, and internal research correspondingly less attractive.

4 The large corporate lab and the innovation ecosystem

We began this chapter by noting the rise and fall of American productivity growth in the twentieth century. We also noted that the fast growth in the middle of the century was associated with important innovations, often developed in large corporate labs. Sections 2 and 3 documented an interesting additional fact: the rise and fall of American growth largely coincided with the rise and fall of the large corporate lab.

In this section, we suggest that the large corporate lab may be an important (and often unappreciated) component of a healthy innovation ecosystem. Observers often argue that ecosystems where research is mostly performed by universities and start-ups are nimbler and more efficient than those where large corporations and their labs play a more important role. While we do not deny that there might be gains from specialization when innovative labor is more finely subdivided, we also point out that there might be social costs associated with the demise of the large corporate lab. We highlight two issues: (i) that inventions originating from large corporate labs may be different from those originating from universities and start-ups, and that (ii) corporate labs may generate significant positive spillovers by spurring high-quality scientific entrepreneurship. The risk we highlight is that, although large corporations are withdrawing from internal research because it is no longer privately profitable, this change may not be positive for society.

4.1 Inventions originating from large corporate labs are different

There are several reasons why large corporate labs may develop inventions that are different from those produced by universities and start-ups.

4.1.1 Corporate labs are multi-disciplinary and have more resources

Inventions by large corporate labs may differ from inventions by universities or start-ups because large firms have access to greater financial resources and can tackle multidisciplinary problems by integrating multiple knowledge streams and capabilities (Tether, 1998; Pisano, 2010). The transistor, for instance, would not have been possible without the blend of theoretical prowess and engineering skills available at Bell Labs. Attempts at solid state electronics had been made since the early 1940s by Purdue physical chemist Karl Lark-Horovitz, General Electric, and others. Only Bell Labs, however, had the interdisciplinary team of physicists, metallurgists and chemists necessary to solve the many theoretical and practical problems associated with developing the transistor.

Because MIT's Radiation Lab during World War II had selected AT&T's Western Electric to manufacture back-voltage rectifiers for radars, metallurgists at the firm had gained first-hand experience in purifying and doping semiconductors. Bell metallurgist Henry Theurer later developed the method of zone refining in 1951, which processed germanium crystals to impurity levels as low as one part in ten billion. It was also at Bell that Gordon Teal's crystal "pulling" method fabricated the positive-negative junctions in silicon rods, and Shockley's transistor would not have been possible to invent without either one of these two in-house achievements in material sciences (Gertner, 2013).

Similarly, Holbrook et al. (2000) note that it was cross-functional coordination between R&D and manufacturing that led to Fairchild's two major breakthroughs: the planar process and integrated circuits. In contrast, fabless firms, which specialize on the design of integrated circuits while avoiding the high costs of building and operating manufacturing facilities, would arguably find it hard to come up with these types of innovations.

4.1.2 Corporate labs work on general purpose technologies

Because corporate labs are typically owned by large integrated incumbents, they may have strong incentives to focus on systemic or architectural innovations. Consistent with this, Kapoor (2013) finds that, following vertical disintegration in the semiconductor industry, integrated incumbents reconfigured their activities more towards systemic innovations (which require extensive coordination and communication across different stages of production and actors) and less towards autonomous innovations (which require relatively little adjustment). Lecuona Torras (2017) also finds that large firms were more likely to leverage general purpose technologies to introduce architectural innovations in mobile telephony handsets. Anecdotal evidence support this behavior: Claude Shannon's work on information theory, for instance, was supported by Bell Labs because AT&T stood to benefit the most from a more efficient communication network (Gertner, 2013). IBM supported milestones in nanoscience by developing the scanning electron microscope, and furthering investigations into electron localization, non-equilibrium superconductivity, and ballistic electron motions because it saw an opportunity to pre-empt the next revolutionary chip design in its industry (Gomory, 1985; Rosenberg, 1994, p.258). Finally, a recent surge in corporate publications in Machine Learning suggests that larger firms such as Google and Facebook that possess complementary assets (user data) for commercialization publish more of their research and software packages to the academic community, as they stand to benefit most from advances in the sector in general (Hartmann and Henkel, 2019).

4.1.3 Corporate labs more readily respond to commercial necessity

Research conducted in corporate labs is directed toward solving specific practical problems. This orientation toward specific missions can restrict researchers' freedom, but also reduces the risk of purely theoretical ruminations, and hastens the translation of science to commercial applications. Moreover, unlike small firms that often scramble for survival, large labs can provide researchers with resources and some slack, which may lead to truly path-breaking research. Thus, corporate labs may integrate the best of both worlds. On the one hand, their research is connected to real problems, so that their results are likely to have important industrial applications. On the other hand, this connection is not so strong that the results lie towards the most applied end of the spectrum, and have only limited scientific value. Vannevar Bush observed in 1945 that "Industry is generally inhibited by preconceived goals, by its own clearly defined standards, and by the constant pressure of commercial necessity." However it is often "commercial necessity," or mission orientation, that forces firm research to mobilize science in search of practical solutions.

Even research at Bell Labs that did not yield any forseeable applications were motivated by practical considerations. The discovery of cosmic microwave background radiation (CMBR) by Bell Labs physicist Arno Penzias and radio astronomer Robert Wilson in 1959 (for which the pair won the Nobel Prize for Physics in 1978), for instance, did not have any foreseeable industrial application. However, Bell's Holmdel Horn Antenna which picked up CMBR was originally devised in service of the Echo Satellite program at AT&T to better detect radio signals from outer space. Andrew Odlyzko underlines the importance of commercial necessity at Bell:

> "It was very important that Bell Labs had a connection to the market, and thereby to real problems. The fact that it wasn't a tight coupling is what enabled people to work on many long-term problems. But the coupling was there, and so the wild goose chases that are at the heart of really innovative research tended to be less wild, more carefully targeted and less subject to the inertia that is characteristic of university research."[12]

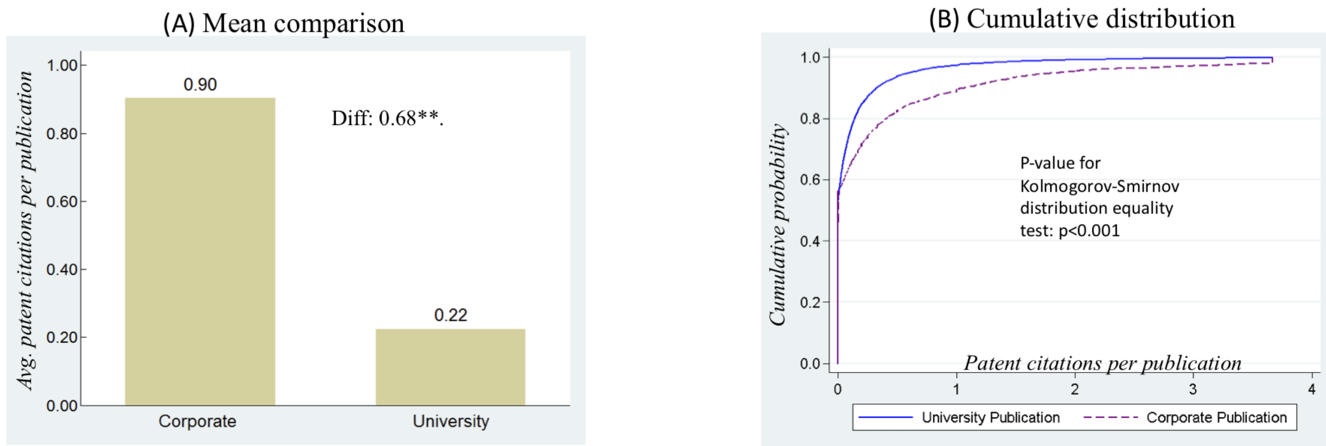
An example that sums up the three axes of differentiation of large corporate lab research from university and startup research is given by Google's 2016 project to apply deep neural networks on their translation service (Lewis-Kraus, 2016). Google Brain (the Artifical Intelligence research arm of the firm) had some success with isolated research projects such as Andrew Ng's "cat paper" in 2012 (which used convoluted neural networks to classify feline images from Youtube videos) (Le et al., 2011). However, the machine learning field was also advancing rapidly. In the same year, Geoffrey Hinton's team at Toronto had pulled down the classification error rate in the ImageNet

[12] Letter to the *Wall Street Journal*, available at http://www.dtc.umn.edu/ odlyzko/misc/wsj-bell-labs-20120326. Accessed 18/02/2019

competition under 25% for the first time by using neural networks, a relatively underappreciated algorithm throughout the preceding decade. Google had founded Google Brain in the early 2010s with practical objectives in mind: machine recognition of feline images was not simply an academic exercise, but was applied later to automatic character recognition in Google books, named object recognition in Google photos and Google maps. Moreover, Google's wherewithal and engineering skills were leveraged heavily in the following research project to patch Google Translate. In 2014, University of Montreal's Yoshua Bengio and Google's Quoc Le both theoretically validated that it was possible to apply neural networks using word embeddings. However, because the data size and processing power to train a model to translate between languages was immense, the Google Brain team tasked with implementing the new approach had to make use of thousands of Graphical Processing Units (GPUs) and Google's proprietary Tensor Processing Units (TPUs). Because neural network implementation at this scale was unprecedented, the TPU chips needed to be debugged by the Google Brain team along with the hardware teams at Google. This iterative development process would have been difficult to achieve across organizational boundaries, since incentives may not align and communication delayed. A corporate laboratory such as Google Brain could relatively easily marshal various scientific disciplines and downstream manufacturing capability early on in the research process, which increased the likelihood of introducing a workable proof of concept product at the end.

A consequence of large corporate research being i) more interdisciplinary, ii) wider in scope, yet iii) closely coupled with practice is that on average, corporate scientific research will be more useful to inventors than university research. If this is the case, then we should observe inventors of patents, for instance, devote more attention to them than to academic counterparts. As mentioned above, Bikard (2015) finds corporate publications to be 23% more likely to be cited than university publications one the same scientific discovery. More recent evidence also shows that patents which cite industry publications such as the IBM Technical Disclosure Bulletin (TDB) are associated with higher quality as measured by forward patent citations, compared to others in the same patent class (Bhaskarabhatla et al., 2019). We add wider correlational evidence in support of this prediction by comparing the likelihood of a U.S. utility patent issued between 1980 and 2006 citing a corporate scientific publication versus a university counterpart in its non-patent literature section. Using a

Figure 14: Patent Citation to University vs. Corporate Publications



Note: The sample includes publications from the top 100 U.S. universities and corporate publications of our sample firms that were published over the sample period (1980-2006) and covered in Web of Science "Science Citation Index" and "Conference Proceedings Citation Index-Science." Patent citations per publication is measured by total citations (internal and external) per publication by corporate and non-corporate patents granted between 1980 and 2014. Figure A presents mean comparison for university vs. corporate publications by patent citation received per publication. Figure B, plots the cumulative distribution of patent citations received per publication, by corporate and university publications. Number of patent citations per publication is presented with a proximity value in the 99th percentile of the sample. Analysis is from Arora et al. (2017)

linear probability model, we estimate that corporate publications are on average 11% more likely to be cited as a university publications. We control for the possibility that these results are driven by lower-quality universities, "applied" journals, or industry level differences in scientific quality, and find that the results hold. Panel (A) of figure 14 visualizes the citation likelihood differences between these two groups, while panel (B) shows that corporate publications first order stochastically dominate university publications in terms of the number of citations they receive from patents.

4.1.4 Large corporate labs may generate significant external benefits

Beside developing inventions that may not be created otherwise, large corporate labs have also generated significant external benefits. One well-known example is provided by Xerox PARC. Xerox PARC developed many fundamental inventions in PC hardware and software design, such as the modern personal computer with graphical user interface. However, it did not significantly benefit from these inventions, which were instead largely commercialized by other firms, most notably Apple and Microsoft. While Xerox clearly failed to internalize fully the benefits from its immensely creative lab (especially when the industries affected were unrelated to Xerox's core business), it can hardly be questioned that the social benefits were large, with the combined market capitalization of Apple and Microsoft now exceeding 1.6 trillion dollars.

Another potentially important class of external benefits generated by corporate labs is spin-off activity. Klepper (2015) systematically documented the importance of spin-offs in the U.S. innovation ecosystem. He found that in many high-tech industries, including the early automobile industry, semiconductors and lasers, spin-offs were exceptional performers. One extreme example is Fairchild Semiconductor, whose spin-offs arguably led to the creation of Silicon Valley. Agrawal et al. (2014) also find a large innovation premium in regions where numerous small patenting entities coexist with at least one large patenting entity.

A surprising implication of this analysis is that the mismanagement of leading firms and their labs can sometimes be a blessing in disguise. The comparison between Fairchild and Texas Instruments is instructive. Texas Instruments was much better managed than Fairchild but also spawned far fewer spin-offs. Silicon Valley prospered as a technology hub, while the cluster of Dallas-Fort Worth semiconductor companies near Texas Instruments, albeit important, is much less economically significant. Arguably, spin-off driven growth encouraged diversity and innovation far more than the efforts of a well-run Fairchild could have. Similarly, attempts to centralize and direct innovation activity may backfire. This was the case for Xerox's spin-offs. As documented by Chesbrough (2002, 2003), the key problem there was not Xerox's initial equity position in the spin-offs, but Xerox's practices in managing the spin-offs, which discouraged experimentation by forcing Xerox researchers to look for applications close to Xerox's existing businesses. Again, the coexistence between islands of centralized control—the large corporate labs—and markets populated by a variety of start-ups and spin-offs, seems most conducive to fast experimentation and growth.

To summarize, corporate research leverages a substantial amount of resources, is eclectic and geared more toward practical problem solving. However, as already noted, managing research inside corporations so as to produce value is very difficult. Even after Wallace Carothers' team "cold–drew" nylons, it took six years until full-scale commercial production (Hounshell, 1988). DuPont's previous expertise with textile processing and fiber manufacture accumulated at the rayon department needed to be integrated with subsequent process improvements that would make industrial production possible. Infighting and competition also needed to be tamed – Reynold Johnson, who ran IBM's San Jose laboratory, insisted to his engineers that "It is your most important assignment in this laboratory to give assistance when you are asked to do so, by any other engineer of this staff, in the form of consultation, experimentation, or suggestions, and the second most important assignment is that of carrying on the project which you are assigned" (Pugh, 1995, p.223). IBM management also instituted over a dozen "joint programs" in which "technology transfers" could occur between scientists at Watson and product development personnel (Gomory, 1987), which is a model that is similar to the "hybrid" research management system that Google has also employed, perhaps because of the role of IBM research alumni such as Al Spector (Spector et al., 2012).[13]

5 The policy environment

In this section, we briefly discuss some effects of public policy on the American innovation ecosystem.

5.1 Antitrust

As noted in Section 2.2, one factor that historically motivated many large firms to establish or expand their labs was antitrust pressure. In the early and mid-twentieth century, concerns about excessive concentration of economic and political power in the hands of dominant firms helped constrain the ability of large firms to grow through mergers and acquisitions. During this period, if large firms wanted to grow, they often had little choice but to invest in internal R&D.

Antitrust policy not only encouraged large firms to invest in internal R&D, but also occasionally promoted technology diffusion. A leading example is the 1956 consent decree against the Bell System, one of the most significant antitrust rulings in U.S. history (Watzinger et al., 2017). The decree forced Bell to license all its existing patents royalty-free to all American firms. Thus, in 1956, 7,820 patents (or 1.3% of all unexpired U.S. patents) became freely available. Most of these patents covered technologies that had been developed by Bell Labs, the research subsidiary of the Bell System.[14]

[13]Indeed, simply collocating a research organization within a firm is woefully insufficient to translate knowledge into products. Xerox PARC's Alto computer, for instance, was developed by the brightest minds in GUI design such as William English and Alan Kay, who pioneered concepts in bitmapping and wrote the first object-oriented programming language *smalltalk* to control multiple operations. Yet, at $10,500 per machine, the Altos were not marketed to the public and further plans for Alto II and IIIs were quashed by Xerox headquarters. The Xerox Star, which made its market debut in 1981, was discontinued in 1985 due to its high price point of $16,500. Xerox was given a full decade until it faced credible competition from the Apple Lisa (1983) and Macintosh (1984), but was unable to effect the process improvements to bring price to a competitive level (Hiltzik, 1999). Much like a university project, only 2,000 Altos were built chiefly for internal use. This "visible hand" of goal-oriented research management is therefore unlikely to arise simply from collocation in the new innovation ecosystem save for specific government initiatives.

[14]Moser and Voena (2012) also find that compulsory licensing spurs innovation. They examine compulsory licensing

Compulsory licensing substantially increased follow-on innovation building on Bell patents. Using patent citations, Watzinger et al. (2017) estimate an average increase in follow-on innovation of 14 percent. This effect was highly heterogeneous. In the telecommunications sector, where Bell kept using exclusionary practices, there was no significant increase. However, outside of the telecommunications sector, follow-on innovation blossomed (a 21% increase). The increase in follow-on innovation was driven by young and small companies, and more than compensated Bell's reduced incentives to innovate. In an in-depth case study, Watzinger et al. demonstrate that the decree accelerated the diffusion of the transistor technology, one of the most important technologies of the twentieth century.

This view that the consent decree was decisive for U.S. post-World War II innovation, particularly by spurring the creation of whole industries, is shared by many observers. As Gordon Moore, the co-founder of Intel, notes: "[o]ne of the most important developments for the commercial semiconductor industry (...) was the antitrust suit filed against [the Bell System] in 1949 (...) which allowed the merchant semiconductor industry "to really get started" in the United States (...) [T]here is a direct connection between the liberal licensing policies of Bell Labs and people such as Gordon Teal leaving Bell Labs to start Texas Instruments and William Shockley doing the same thing to start, with the support of Beckman Instruments, Shockley Semiconductor in Palo Alto. This (...) started the growth of Silicon Valley" (Wessner (2001, p.86) as quoted in Watzinger et al. (2017)).

Scholars such as Peter Grindley and David Teece concur: "[AT&T's licensing policy shaped by antitrust policy] remains one of the most unheralded contributions to economic development possibly far exceeding the Marshall plan in terms of wealth generation it established abroad and in the United States" (Grindley and Teece (1997) as quoted in Watzinger et al. (2017)).

Starting from the 1980s, antitrust pressures abated and growth through acquisitions returned to be a viable alternative to internal research. The incentives to invest in internal research correspondingly declined. However, as giants such as Google, Facebook and Amazon continue to grow and amass market power, political backlash and more intense antitrust scrutiny may return. Just like DuPont and Bell in the twentieth century, these new economy giants may view research and its military and/or geopolitical implications as an insurance policy against aggressive antitrust enforcement.

after World War I under the Trading with the Enemy Act to identify the effects of compulsory licensing on domestic (U.S.) invention. Their analysis of nearly 130,000 chemical inventions suggests that compulsory licensing increased domestic invention by 20 percent.

5.2 Bayh-Dole and university research

There are a slew of policy inducements to research, development and commercialization. Here we focus on one that relates to commericalization of university research, the Bayh-Dole Act, dubbed the "[P]ossibly the most inspired piece of legislation to be enacted in America" by The Economist.[15] The Bayh-Dole Act was enacted by Congress in 1980 with the goal of facilitating the commercialization of university science. The law eliminated U.S. Government claims to university-based innovation, giving U.S. universities the rights to inventions that were federally funded. While we remain agnostic on the extent of inspiration (or lack thereof) behind other legislations enacted in America, it is unlikely that Bayh-Dole will be sufficient to fill the gap left by the withdrawal of corporations from research.

The evidence on whether altering the property rights associated with an invention encourages the commercialization of university science is mixed. For instance, despite U.S. university patenting rates being approximately five times larger in 1999 than in 1980, Mowery and Sampat (2004) find no evidence that Bayh-Dole caused a structural break in the preexisting trend. Using a larger dataset than previously available, Ouellette and Tutt (2019) reexamine the question of whether higher inventor royalty shares lead to greater patent-related activity. They do not find that increasing the inventor's share of patent licensing revenue in official royalty-sharing policies causes academics to patent more. They also examine moves between universities by the most active university patenters. Based on 130 lateral moves for which they could calculate the expected share at both the old and new institution at the time of the move, they reject the hypothesis that high-patenting academics tend to move to schools with a higher expected share.

In contrast, Hvide and Jones (2018) find that the allocation of property rights have an important effect on innovation. They examine the end of the "professor's privilege" in Norway. Upon implementing the reform, Norway effectively moved from an environment where university researchers had full ownership of their inventions (the "professor's privilege"), to a system where inventors, just like in the U.S. today, only holds a minority of the property rights (and the university holds the remainder). The reform had the opposite effect as intended. The shift in rights from researcher to university reduced both the quantity and the quality of inventions. It led to an approximately 50 percent drop

[15]Source: https://www.economist.com/technology-quarterly/2002/12/12/innovations-golden-goose

in the rate of start-ups by university researchers. Patent rates fell by broadly similar magnitudes. University start-ups exhibited less growth and university patents received fewer citations after the reform, compared to controls. Overall, the reform, by reducing researchers' ownership stakes, appear to have discouraged university innovation.

Therefore, although Bayh-Dole may well have enhanced engagement in commercialization activity by university researchers, the effect appears to have been small. Further, the proposed mechanism relies heavily on startups and university spinoffs being responsible for developing university inventions, relying upon private investors or venture capital for support. In so doing, not only is the rate of technical advance affected, but also its direction.

5.3 Mission oriented agencies

Corporate labs play an important role in the U.S. innovation ecosystem because their research is directed toward solving specific practical problems. This focus on the potential applicability of research results, however, is not a unique feature of corporate labs.

Mazzucato (2018, p.804) defines mission-oriented policies "as systemic public policies that draw on frontier knowledge to attain specific goals." These goals are advanced by agencies such as the National Institutes of Health (NIH), the Defense Advanced Research Projects Agency (DARPA), and the Advanced Research Projects Agency-Energy (ARPA-E). Mission-oriented agencies have grown to dominate public funding of science in the U.S. (Mowery, 1997; Sampat, 2012). For instance, in 2008 the NIH alone was responsible for funding nearly 30% of all U.S. medical research.

Azoulay et al. (2019) discuss the distinguishing features of the "ARPA model" for research funding. First, it must be possible to organize the domain of research around a technology-related mission or a set of overarching goals. The mission of DARPA, for instance, is "to make pivotal investments in breakthrough technologies for national security."[16] Azoulay et al. (2019, p.88) note that "the ARPA model is optimized for technical areas that reside in nascent S-curves — the technology exists, is relatively unexplored, and has great potential for improvement." ARPA-ble research is distinct from basic research because it is mission oriented, and also different from pure applied research because its focus is not on incremental advances, but "transformational change." ARPA-funded projects may

[16] Source: https://www.darpa.mil/about-us/mission

involve advancing the scientific frontier, but this is incidental to the main goal — to make significant technological advancements.

To achieve their goals, ARPA agencies collaborate with universities, government labs, and small and large firms in the innovation ecosystem. DARPA funding has been instrumental in supporting especially the growth of small technology firms, which were quick to recognize the importance of innovation for their viability and tended to be more responsive to small grants than larger defence contractors (Mazzucato, 2015). Military procurement more broadly played a key role in spurring spinoff and startup activity in many science-based industries, such as semiconductors and lasers. In the 1960s, DARPA even supported the creation of scientific and technological human capital by funding the establishment of new computer science departments in various U.S. universities, such as Carnegie Mellon. Also important, "DARPA officers engaged in business and technological brokering by linking university researchers to entrepreneurs interested in starting a new firm; connecting start-up firms with venture capitalists; finding a larger company to commercialize the technology; or assisting in procuring a government contract to support the commercialization process" (Mazzucato, 2015, p.77). Mazzucato concludes that, by taking advantage of this new ecosystem, "the government was able to play a leading role in mobilizing innovation among big and small firms, and in university and government laboratories" (2015, p.77).

Evaluating the impact of mission-oriented agencies and their funding on technological change is difficult. DARPA has been praised not just for the development of important military technologies (e.g., precision weapons, stealth technology), but also for having contributed to fundamental civilian innovations such as the Internet, automated voice recognition, language translation and Global Positioning System receivers. As argued earlier, the significant increase in federal funding for biomedical research through the NIH, from \$2.5 billion in 1980 to \$29 billion in 2015, also most likely contributed to U.S. life science companies not withdrawing from scientific research, unlike firms in other sectors.[17]

In an environment where large firms are withdrawing from internal research, it is likely that the importance of mission-oriented agencies in supporting public and private research may grow

[17] Azoulay et al. (2018) find that NIH funding spurs the development of private-sector patents: an additional \$10 million in NIH funding for a research area generates 2.7 additional private-sector patents. Fully half of the patents resulting from NIH funding are for disease applications distinct from the one that funded the initial research. Using estimates for the market value of patents taken from the literature they find that a \$10 million increase in NIH funding yields \$30.2 million in firm market value. Using mean present discounted value of lifetime sales for new drugs, they estimate that a \$10 million increase in funding would generate between \$23.4 and \$187.4 million in sales.

even further. Mazzucato (2018) and Azoulay et al. (2019) provide valuable insights on how mission-oriented agencies should be staffed, organized and managed to produce maximum societal impact.

6 Conclusion

During the so-called Golden Age of American Capitalism, large corporate labs were important loci of research, and important sources of scientific and technical advances. At the start of the period, the university research sector was small (certainly compared to the current period) and uneven in quality. Over time, university research grew, bolstered by significant support from the federal government. This period also coincided with (and perhaps this was more than a coincidence) incumbent firms enjoying significant market power but restrained by aggressive anti-trust actions.

Despite the apparent successes, corporate research, and the large corporate labs in particular, fell out of favor with investors, and eventually also, with managers. The focus shifted to university research, and startups, often venture funded, that aimed to capitalize on the scientific and technical advances in university labs. Corporations turned to sourcing ideas and inventions from the outside, hoping to combine it with their downstream development and commercialization abilities.

These hopes have not been fully realized, at least not yet. Even as this division of innovative labor has progressed, so have the challenges it faces become more evident. University research is different from corporate research: It is less likely to be mission-driven. Its smaller scale and greater disciplinary focus meant that university research typically produces insights, which then need further development and integration to produce commercializable inventions. This requirement of converting insight to product has proved more onerous and challenging than commonly appreciated.

It seems unlikely that corporate research will rediscover its glory days. The boost in employment of data scientists, machine learning experts, and even economists, in large firms would appear to prognosticate a different future. We disagree. For some time, quick wins from low-hanging fruit (such as optimizing auction or advertising formats) may cover up the problem, but the fundamental challenge of managing long-run research inside a for-profit corporation remains a formidable one. Put differently, although there are significant efficiency gains that companies have realized from hiring data scientists and economists, there are only a handful of cases of significantly new markets created from such efforts, and incumbent firms continue to rely on outside inventions to fuel their growth. In the longer run, therefore, university research will remain the principal source of new ideas for such inventions. And therefore the ongoing economic experiments of discovering efficient ways to translate scientific insights in universities into technical advances that eventually manifest in productivity growth will remain crucial to our future prosperity.

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