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# The Changing Structure of American Innovation: Some Cautionary Remarks for Economic Growth

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### Executive Summary

A defining feature of modern economic growth is the systematic application of science to advance technology. However, despite sustained progress in scientific knowledge, recent productivity growth in the United States has been disappointing. We review major changes in the American innovation ecosystem over the past century. 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 a form that can be readily digested and turned into new goods and services. Small firms and university technology transfer offices cannot fully substitute for corporate research, which had previously integrated multiple disciplines 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 has also slowed, at least for a period of time, the transformation of that knowledge into novel products and processes.

### I. 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 fibers, 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).

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978-0-226-70727-3/2020/2020-0200$10.00

However, despite sustained increases in the quantity of scientific knowledge, 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 gross domestic product (GDP) per hour (i.e., labor productivity) grew substantially in the middle of the twentieth century, from 1.79% per year between 1870 and 1920 to 2.82% per year between 1920 and 1970. However, in the most recent period (1970–2014), productivity grew by a modest 1.62% per year. Gordon concludes that productivity rose between 1920 and 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 sustained expansion of scientific input (measured in terms of research dollars spent) and output (measured by academic articles published) from American academia, as shown in figure 1.[1]

Gordon (2016) attributes the rapid pace of technological progress between 1920 and 1970 to the development and extension of earlier

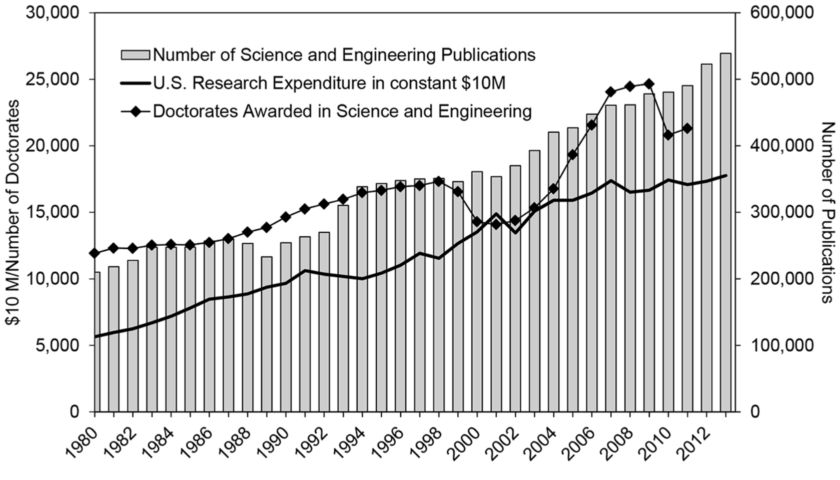

**Fig. 1.** US scientific investment and output (1980–2013)

Note: Doctorates awarded in science and engineering (S&E) are calculated from the NSF's Survey of Earned Doctorates and excludes degrees in the social sciences. Number of S&E publications is from the Clarivate Web of Science and includes all scientific articles in the Science Citation Index—Expanded (SCI—EXPANDED) and Conference Proceedings Citation Index-Science (CPCI-S) with a US author from 1980 to 2013. US research expenditure figures are calculated from the *National Patterns of R&D Resources: 2014–15 Data update, NSF 17-311*, tables and include both basic and applied research expenditure. Figures are adjusted to 2016 dollars using GDP deflator from the World Bank National Accounts data set.

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 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. (Gordon 2016, 571–72)

By the 1980s, however, many corporations began to look to universities and small start-ups for ideas and new products.[2] Large corporations' reliance on externally sourced inventions grew, and many leading Western corporations began to withdraw from scientific research (Mowery 2009; Arora, Belenzon, and Patacconi 2018). Some corporate labs were shut down and others spun off as independent entities. Bell Labs had been separated from parent company AT&T and was 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 redirected research toward more commercial applications in the mid-1990s (Bhaskarabhatla and Hegde 2014).[3] A more recent example is DuPont's closing of its Central Research and Development Lab in 2016. Established in 1903, DuPont research rivaled that of top academic chemistry departments. In the 1960s, DuPont's central research and development (R&D) unit published more articles in the *Journal of the American Chemical Society* than Massachusetts Institute of Technology (MIT) and California Institute of Technology (Caltech) combined. However, in the 1990s, DuPont's attitude toward research changed and after a gradual decline in scientific publications, the company's management closed its Central Research and Development Lab in 2016.[4]

These examples are backed by systematic evidence. National Science Foundation (NSF) data indicate that share of research (both basic and applied) in total business R&D in the United States fell from about 30%

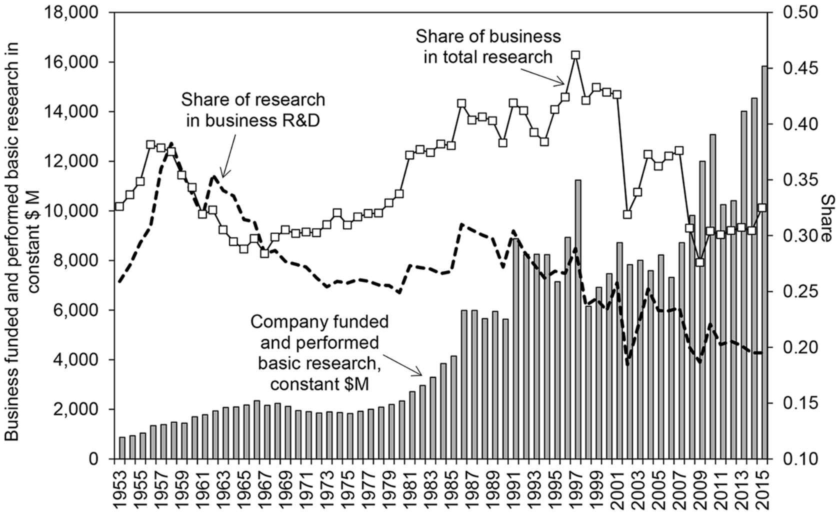

**Fig. 2.** Business funded and performed research in the United States (1953–2015)
Note: Data for this graph are sourced from the *National Patterns of R&D Resources: 2014–15 Data update, NSF 17-311*, from the National Science Foundation, National Center for Science and Engineering Statistics. 2017. Arlington, VA. Available at https://www.nsf.gov/statistics/2017/nsf17311.

in 1985 to below 20% in 2015 (fig. 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 and 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 performed in American listed firms. The authors also find that the drop is even more dramatic for established firms in high-quality journals. For articles within the top quartile of journal impact factor scores, the magnitude of the drop increases to more than 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 fig. 6). This evidence points to the emergence of a new division of innovative labor, with universities focusing on research, large firms focusing on development and commercialization, and spin-offs, start-ups, and university technology licensing offices responsible for connecting the two.

In this chapter, we suggest that this division of innovative labor has not, perhaps, 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. Spin-offs, start-ups, and university licensing offices have not fully filled the gap left by the decline of the corporate 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 direct their research toward solving specific practical problems, which makes it more likely for them to produce commercial applications. University research has tended 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 that have proved to be difficult to replace.

Large corporate labs, however, 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 nonexperts. As a result, research inside companies can only survive if insulated from the short-term performance requirements of business divisions. However, insulating research from business also has perils. Managers, haunted by the specter of Xerox PARC and DuPont's "Purity Hall," fear creating research organizations disconnected from the main business of the company. Walking this tightrope has been extremely difficult. Greater product market competition, shorter technology life cycles, and more demanding investors have added to this challenge. Companies have increasingly concluded that they can do better by sourcing knowledge from outside rather than betting on making game-changing discoveries in-house.

The way forward, therefore, probably involves improving the efficiency of the existing division of innovative labor because science remains a vital input into invention. 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 measured by stock market valuation and acquisition price. As they also stress, however, whereas the private value of investing in scientific research in-house declined, there is no evidence that the social value of science 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 also advances in science continue to be useful. This is especially true of corporate research. When company research is significantly advantageous because of complements such as specialized equipment or proprietary data, companies will continue to invest in research, especially if they can appropriate enough of the benefits by restricting spillovers to rivals.[5]

The remainder of this chapter is organized as follows. Sections II and III describe the rise of the US scientific-industrial complex. Section IV explains how this ecosystem has changed in recent times. Interestingly, this rise and fall of the large corporate lab matches quite well the rise and fall of American productivity. Section V, 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. Section VI briefly discusses some effects of public policy on the American innovation ecosystem, and Section VII concludes.

## II. The Old Innovation Ecosystem: 1850–1940

Our discussion builds on accounts by Mowery (2009), Mowery and Rosenberg (1998), and others. These authors note that although 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 such inventors and small firms to large corporations and their labs. After World War II, corporate labs reached their zenith, with corporate scientists winning a number of Nobel Prizes. By the 1980s, however, small firms (often founded by university scientists) regained their advantage because the postwar period also saw the rise of the research university. Universities went from merely being the producers of human capital to becoming the dominant producers of scientific knowledge.

### *A. The Age of Independent Inventors and the Market for Technology: 1850–1900*

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 was 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, 14). Even the Smithsonian Institutions did not pursue or support basic scientific research during this era (Shils 1979, 22). The Land Grant Institutions established after the Morrill Act of 1862 were intended to pursue 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, with only 39 papers in mathematics, 154 in physics, and 134 in chemistry (Kevles 1979, 170). Naturally, American inventions in this period relied upon individual creativity, mostly in mechanical design. Lamoreaux and Sokoloff (1999) show that, in the 1840s and 1850s, patents were mostly held by individuals 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, and Western Union employed Thomas Edison for various technical solutions in the 1870s (Birr 1979). By the turn of the century, as the inventive process itself became more science based, firms began to invest more directly in science. Even so, independent inventors remained an important source of inventions in the first half of the twentieth century.

Independent inventors were supported by an active market for technology. By the 1870s, technology transactions were common, particularly in the northeastern United States. On the one hand, Lamoreaux and Sokoloff (1999) estimate that the ratio between patents assigned in 1870 to patents granted in 1870 was 0.83. In 1890 and 1911, the ratio was somewhat lower, at 0.71.[6] On the other hand, the share of patents assigned at issue grew from 18.4% to 31.1%, with an increasing share of assignments going to companies. In other words, a growing share of inventions was being commercialized by selling the patents, especially to existing producers. Simply put, there was an active market for technology in the latter half of the nineteenth century.

The number of individuals specializing in inventions grew as well, consistent with Adam Smith's dictum that specialization is limited by the extent of the market. The share of occasional inventors (who filed one or two patents over their lifetime) from all inventors fell from more than 70% in 1830 to less than 35% in 1870. In 1870, specialized inventors, who filed 10 or more patents over their lifetime, accounted for 5% of all patents. By 1911, their share of a much larger patent pool had grown to 25%. These specialists were also more likely to assign their patents to others, consistent with the view that a growing market for technology and greater specialization in invention went hand in hand during this time.

Corporate engagement in research began modestly. The leading American 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. Instead, railroads and other large firms relied upon acquiring inventions from inventors. In many instances, these inventors worked for the railroad but were not hired to invent (Usselman 1999). 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 troubleshoot production. The patent department of American Bell Telephone, a high-tech enterprise of its day, was responsible for evaluating ideas submitted to it for patenting. Much of its efforts were spent on evaluating external inventions, even though the company acquired only a small fraction of such inventions. Only in 1907 did the emphasis shift to internal R&D, with the appointment of Theodore Vail as president.

Corporate attitude toward the organization of science in for-profit corporations was well expressed in 1885 by T. D. Lockwood, head of American Bell Telephone Company'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, 42). Wise (1985) argues that Westinghouse and Edison Electric followed a similar strategy during the late nineteenth century. In short, these leading companies were purchasing patents and consulting services from independent inventors rather than developing their own R&D facilities.

## B. *The Innovation Ecosystem in Transition: 1900–1940*

### The Beginnings of Corporate Research

Several pushes and pulls propelled American corporations to create large R&D laboratories. First, the German precedent of industrial research in chemical firms allowed for firms such as BASF, Bayer, and Agfa to thrive in organic synthetic dyes in a highly competitive international market (Reich 1985, 41). Second, the strategy of acquiring patents was becoming difficult to implement because of the rising complexity of technologies. For example, DuPont had repeatedly failed in its attempt to use the Bevan, Cross and Topham patents from the United Kingdom to start a viscose rayon process in the United States in the 1910s. It lacked the internal technical and scientific capability to understand these patents and the 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. General Electric's (GE) 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 Carl Welsbach and Walther Nernst, the 1920 Nobel Laureate in Chemistry, respectively, invented incandescent mantels for gas lamps (a substitute product) and a glower that required no vacuum to operate that 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 (GERL) in 1900. The payoffs were not long in coming: William Coolidge in 1906 developed a method using tungsten instead of carbon filaments to increase bulb life, and Irving Langmuir in 1913 invented 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, employed 1,102 scientists in corporate labs in 1921 and grew to 3,255 in 1933 and to 14,066 by the end of World War II (Mowery and Rosenberg 1999). Later, the wartime experiences of being part of the National Research Council (NRC) cemented the faith of managers that science could be effectively put to practical applications (Geiger 2004). 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 that buying other firms would be a costlier way to grow than by introducing new products derived from in-house research. In the

1950s, firms such as AT&T, DuPont, IBM, and Kodak 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 was still aimed at some form of economic problem solving and, hence, fell under the category of "mission-oriented" research. Charles P. Steinmetz's application of complex exponentials to decompose sinusoidal signals, for instance, was motivated by the need to better understand impedance and control alternating currents (Kline 1992). Of course, that industrial research was mission-oriented does not detract from its scientific sophistication (Stokes 2011). Indeed, even at the early stages of industrial research, Steinmetz earned himself the presidency of the American Institute of Electrical Engineers, while Langmuir collected his Nobel Prize in Chemistry in 1932 for work done at GERL.[7] The scientific quality of corporate research remained high even as quantity grew. Quality, as measured by forward citations by scientific peers, kept up with (and at times exceeded) research at top universities, as seen in figure 3.

## The Rise of Research Universities

As shown in figure 4, universities in this era relied heavily on state and industry funding rather than federal funding (Bruce 1987; Geiger 2004). According to the Biennial Survey of Education compiled by the Department of Education, the share of federal funding as a source of university revenue hovered around 4–7% between 1909 and 1939. The share of state funding, however, was 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 who could be employed by the local rubber and tanning industries (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 US Coast Survey, US Geological Survey, and Permanent Commission of the Navy Department (Shils 1979). These form the origins of the "mission-oriented" tradition in US universities.

**Fig. 3.** Scientific citations per publication, by sector (1920–1940)

Note: This graph plots the number of forward scientific citations per publications in Clarivate Web of Science, by the sector of the author's affiliations. "Top Research Universities" include (in alphabetic order) 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 "Industry" sector includes parents and subsidiaries of 200 large industrial firms included in Kandel et al. (2019). 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 received until 2016.

The alternative view of the university as a fundamental research institution driven by intellectual curiosity was 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 University in 1876, Clark University in 1887, and the University of Chicago in 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

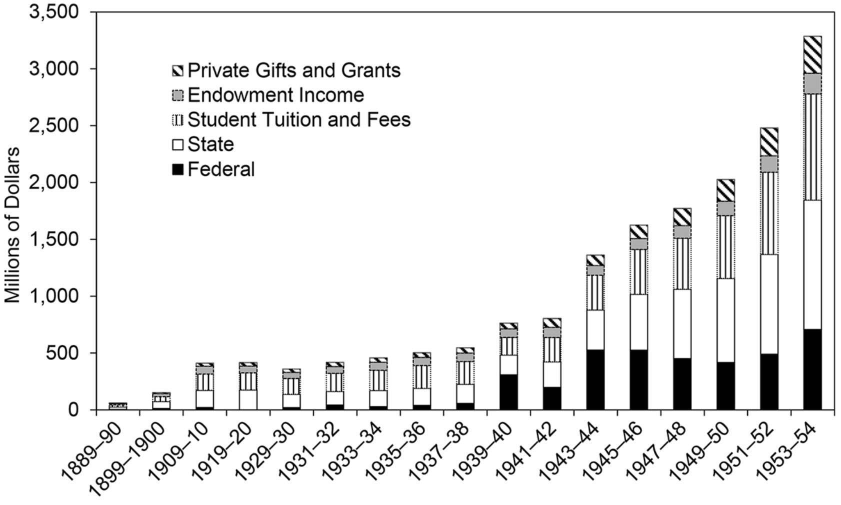

**Fig. 4.** Sources of university revenue in the United States (1889–1954)

Note: This graph plots the sources of revenue for the institutions of higher education in the United States. Data are sourced from Snyder (1993), table 33, and are based on the US 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.

under Wilhelm Ostwald) took up prominent positions at Johns Hopkins and MIT, respectively, and diffused the norm of curiosity-driven science (Reich 1985). Rowland (1883), for instance, authored the "Plea for Pure Science" in 1883 for the American Association for the Advancement of Science (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?" In the view of Rowland and other like-minded scientists, applied science "drives out" basic, and therefore it is imperative that universities defend the latter type (Bush 1945). 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 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 demarcation 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 MIT in 1919 resulted in the "Technology Plan," which would secure corporate financing in exchange for tailor-made conferences and access to alumni files for corporate recruitment.[8]

Another incentive for university faculty to collaborate with industry was that many of the exciting research areas required expensive equipment (e.g., 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, 24), some of the best academic researchers at the time, such as MIT's Willis Whitney and William Coolidge, went to GE 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 that eliminates excess water in chemical reactions, which were critical to the synthesis of large polymers such as nylon. Large companies also 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, 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 5 show that, as compared with 1905, the share of physicists working in industry and government had increased to around 10% in the 1930s. NRC data on scientific employment figures show a similar growth over a slightly later period: scientists and engineers employed in manufacturing industries grew more than 16-fold, from 2,775 to 45,941 between 1921 and 1946 (Mowery and Rosenberg 1999, 22).

However, this pattern of willing university research for industry faced a backlash from within. 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 about industrial 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 led Caltech to shun direct consultancies with firms and to accept only "fluid" grants

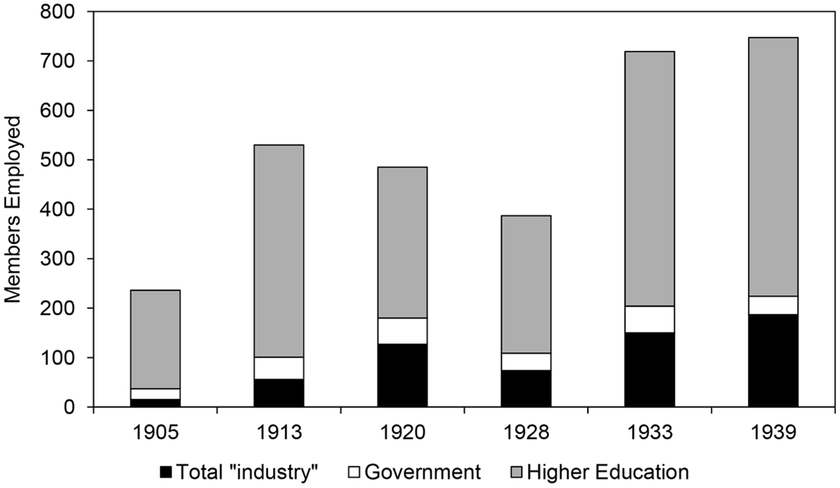

**Fig. 5.** Employment of American Physical Society members

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

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. The University of Chicago similarly wished to withdraw from managing the Metallurgical Lab, which designed an experimental reactor for plutonium production (Geiger 1986, 32). It was largely because of lobbying efforts by lab management and funding by federal agencies that Caltech's Jet Propulsion Laboratory and Applied Physics Lab were able to persist.

## III. The Postwar Period: 1950–1980

### *A. Growing Federal Support for University Research*

The evolution of American research universities since the mid-nineteenth century shows a pendulum swing between mission-oriented and discipline-building research goals. Although 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 members at top research universities were largely pursuing agendas of their own without having to coordinate their efforts with industry.

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, 28). Figure 4 also shows that beginning in 1940, the university sector was 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's 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, 27–29).

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 reorganized under mission agencies such as the Office of Naval Research (ONR), National Institutes of Health (NIH), and National Aeronautics and Space Administration (NASA), while the National Science Foundation (NSF) 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 1935–36 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 gross national product (GNP) grew almost twofold from 0.13 to 0.25 (Mowery and Rosenberg 1993, 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.

### B. *The Golden Age of the Corporate Lab*

This extensive investment in science enabled firms to exchange personnel and ideas with the university sector in the postwar era. Corporate labs, which had been growing substantially during the 1920–40 period, grew even further after World War II. For instance, at its peak in the late 1960s, AT&T's Bell Labs employed 15,000 people, of whom about 1,200 had PhDs (Gertner 2013). Fourteen Bell Labs alumni were awarded the Nobel Prize, and five were recipients of the Turing Award. DuPont also dramatically expanded its research program in the late 1940s, following the discovery and successful development of neoprene and nylon in the 1930s and investigations by the Justice Department's Antitrust Division in the 1940s (Hounshell 1988). DuPont's early successes at innovation cemented the view within the company that research, particularly of the fundamental type, was key to profitability and growth. Antitrust pressures convinced management to invest in internal research rather than relying on technology markets. By the early 1980s, DuPont employed about 6,000 people in its labs, with a research and development budget exceeding a billion dollars supported by sales of about $30 billion. This constituted a 10,000-fold growth in research expenditures and a 1,000-fold growth in sales since the early 1900s (Hounshell and Smith 1988, 9).

Although experimentation and trial-and-error strategies remained key elements of the innovation process, one fundamental change over this time period was the enhanced role of scientific knowledge in guiding new product development. Arguably nowhere was this change more evident than in the pharmaceutical industry. From the late nineteenth century, drug discovery had relied on large-scale, "random" screening of chemical compounds, followed by attempts to improve the molecule and then to test the potential drug candidate for safety and efficacy. However, in the 1960s and 1970s, advances in basic knowledge, instrumentation, and computational capability had made it increasingly valuable for pharmaceutical firms to invest in the fundamental understanding of drugs (Arora and Gambardella 1994; Gambardella 1995). By isolating and understanding the structure of crucial enzymes, for instance, researchers could greatly increase the chances of discovering a chemical agent that would stop a sequence involved in a disease process.

The development of Lovastatin, a breakthrough statin medication used to treat high blood cholesterol and reduce the risk of cardiovascular disease, illustrates how this more science-based approach to drug discovery was adopted at Merck Research Laboratories (MRL) in the 1970s (Vagelos and Galambos 2004). Researchers at various laboratories had identified the enzyme HMG-CoA reductase that controlled the slowest reaction in the cholesterol synthetic sequence. This rate-limiting enzyme was a natural target for inhibition because it controlled the rate of the entire sequence. Through random screening, MRL researchers had also identified a product candidate, halofenate, that lowered blood cholesterol, and the researchers had advanced it to clinical testing in patients. Many researchers at MRL were optimistic about halofenate, but Roy Vagelos, the newly hired MRL president, did not share their optimism. First, this product candidate did not seem to inhibit any of the specific enzymes involved in the cholesterol synthesis. Second, clinical trials had showed that, besides lowering cholesterol, halofenate also had several poorly understood side effects. Vagelos, therefore, decided to prioritize the work of a group of scientists recently hired from Washington University, who were targeting the HMG-CoA reductase enzyme. In 1978, the team discovered that *Aspergillus terreus*, a common soil microorganism, was producing something that was active against the target enzyme. Lovastatin was patented in 1979 and was approved in 1987 for medical use under the brand name Mevacor. In 1986 and 1987 alone, thanks to this more efficient approach to drug discovery, Merck launched seven major new drugs. The gains from these science-based drug discovery methods also translated to improvements in Merck's bottom line: between 1960 and 1989, annual sales increased 30-fold from $218 million to $6.6 billion.

Science-based innovation required corporations to hire a larger numbers of scientists, and universities provided the necessary human capital. The first substantial influx of scientists took place during the 1930s and 1940s, as pharmaceutical firms grew in size and technical sophistication (Mahoney 1959). Furman and MacGarvie (2009) provide evidence that, from 1927 to 1946, research-oriented pharmaceutical firms actively hired from local scientific doctoral programs. Lee (2003) documents very large differences in innovative outputs between the firms that invested in R&D after 1940 and those that did not. Moreover, these differences persisted in the succeeding period between 1940 and 1960.

Even in this "golden age," interactions between corporate labs and other components of the innovation ecosystem—namely, government agencies, universities and start-ups—remained strong. The history of Xerox's Palo Alto Research Center (PARC) provides an illustration of the importance of these interactions (Rao and Scaruffi 2013). PARC was arguably the most innovative corporate research lab in the 1970s, pioneering modern office technology. PARC researchers created the first personal computer with a graphical user interface, the laser printer, and ethernet networking technology. However, many elements of PARC's innovations came from outside, most notably the Augmentation Research Center (ARC) at the Stanford Research Institute (SRI) funded by the Advanced Research Projects Agency (ARPA). The ARC had developed bit-mapped screens, the mouse, hypertext, collaborative tools, and precursors to the graphical user interface in the mid-1960s, long before the private sector had. PARC, which hired many ARC researchers such as Robert Taylor, benefited greatly from the early absorption of these technologies (Hiltzik et al. 1999). Subsequently, however, PARC's innovations also spilled over to other organizations. The story of 24-year-old Steve Jobs visiting PARC in 1979 is well known. Jobs incorporated many key PARC innovations into the Apple Lisa and the Macintosh. Charles Simonyi, after developing the first user-friendly word processor for PARC (the Bravo), also left PARC to take a job at Microsoft, where he oversaw the creation of Microsoft's Office suite of applications. With the benefit of hindsight, Xerox often failed at commercializing technology from PARC. The exception was when the inventions were closely related to its core business (e.g., the laser printer). In those cases, the firm was able to profit handsomely from PARC inventions. Such inventions, at least for a time, allowed the firm to recoup its investment in PARC despite the errors and spillovers.

Another illustration of the interactions between elements of an innovation ecosystem is provided by the early development of laser technology. The main theoretical work leading up to the laser was coauthored by a university scientist (Columbia's Charles Townes) and a corporate researcher (Bell Labs' 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 (Hecht 1992; Gertner 2013). Universities, however, 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 numerous 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, 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, its 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 used today in fiber-optic data links (Guenther, Kressel, and Krupke 1991).

In summary, the innovation ecosystem that emerged after World War II saw a sustained growth of the research university sector, spurred by the infusion of 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. During this time, corporations were also, perhaps unfairly, often blamed for failing to exploit the many inventions created in their labs. As research universities continued to expand, corporations' ability to source inventions from outside also grew. These changes made it increasingly difficult for firms to justify large investments in internal research. A drastic transformation of the American innovation ecosystem ensued, beginning in the last quarter of the twentieth century.

## IV. 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 commercial objectives, individual scientists subdivided problems into smaller problems, with each subproblem more amenable to scientific investigation. From an industry perspective, however, using the output of university research still required significant coordination and integration. The task of converting scientific insights into inventions that could be the basis of new products and processes became specialized. Universities were not well placed to "translate" research findings into executable solutions. Corporations, especially those that lacked internal labs familiar with mission-oriented research, also found translation difficult. Thus, although specialization had its benefits, the separation between upstream research and downstream applications also presented formidable challenges.

### *A. Universities, the Division of Innovative Labor, and the Market for Technology*

During the 1980–2016 period, the research university sector continued to grow at a sustained pace. Academic institutions and nonprofits spent around $80 billion on basic and applied research in 2015 (fig. 6.). Their share of total research in 1985 was 23.8% and rose to 33.6% in 2015 (Boroush 2017). Universities participated in the division of innovative labor by producing scientific insights, as well as by directly producing inventions to be developed. In support of such a division of labor, the

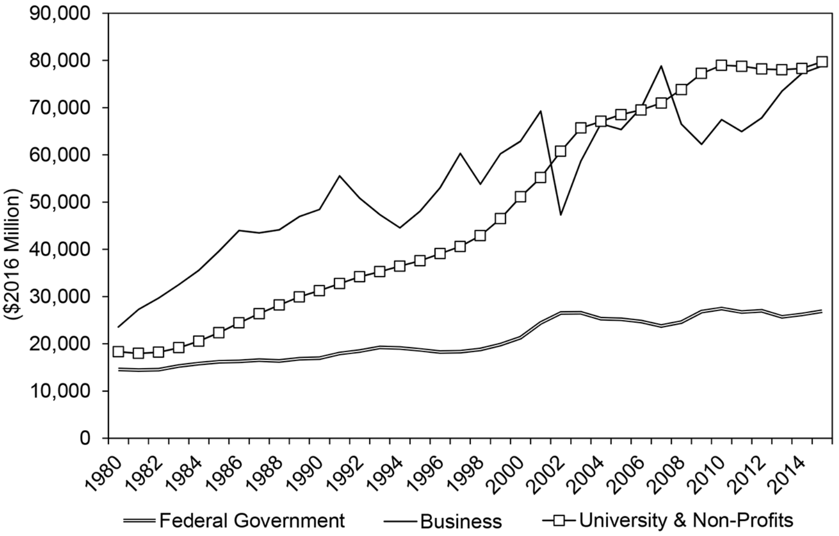

**Fig. 6.** US applied and basic research expenditure by performing sector (1980–2015)
Note: This figure plots the aggregated annual basic and applied research expenditure by performing sector from the *NSF National Patterns of R&D Resources (2014–15)*, tables 3 and 4. Figures are adjusted to 2016 dollars using GDP deflator from the World Bank National Accounts data set.

US Congress passed the National Cooperative Research Act in 1984, which reduced the risk of antitrust prosecution by the Department of Justice (DOJ) for firms engaging in R&D collaborations. Perhaps the most widely commented on reform of this era was 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 World War II, 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 28,000 patents (Markel 2013). However, only a few of these inventions actually made it into the market. One of the expected benefits of the Bayh-Dole Act was to facilitate the development of these underutilized resources by transferring property rights to the universities, which would then be able to independently license the rights at the going market rate. Licensing, joint ventures, or spin-offs from university research were, of course, 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.

Universities responded by deepening their participation in invention. The share of universities in patenting activity increased from 1% of total patents in 1975 to 3.6% in 1990. The ratio of patents to R&D spending in universities almost doubled during this period, from 57 patents per $ billion to 96 patents per $ billion. Because the rest of the economy saw a decrease from 780 to 429 patents per $ billion of R&D spending, it is unlikely that this increase in patent intensity reflected changes in patent office practices or other reductions in the cost of patenting (Arora, Fosfuri, and Gambardella 2004). Over a longer period of time, the number of patents granted exhibits an even starker contrast: 380 patents were awarded in 1980, whereas 3,088 were awarded in 2009 (Markel 2013). The increases in university patent applications and gross licensing income shown in figure 7 underline this upward trend. The number of university patent applications more than quintupled between 1995 and 2015 from around 2,700

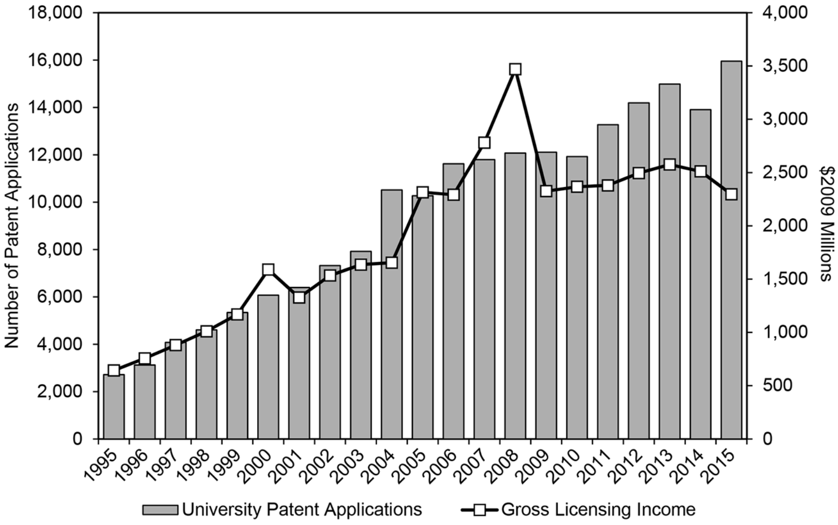

**Fig. 7.** Patent applications and gross licensing income by universities (1995–2015)

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

to more than 15,000 per year. A similar trend is observed for university licensing income, which jumped from $0.6 billion to $2.3 billion in the same period. University scientists have found it increasingly attractive to start their own businesses, with high-powered incentives and fast decision making that are difficult to replicate in large, established firms. Changes in the institutional and legal environments complemented these trends. Start-ups can now get financing from venture capitalists and from the Small Business Innovation Research (SBIR) and other government programs (Lerner 2000; Mazzucato 2015). Indeed, many firms have been spun off from nonprofit research institutions bringing forth such innovations as magnetic resonance imaging (MRI), recombinant hepatitis B vaccine, atomic-force microscope, and the Google pagerank algorithm.

Cultural changes in whether university research should be used in industry were also important in shaping university participation in markets for technology (MFT). In the 1960s and 1970s, university-industry collaborations were seen with suspicion. Geiger (1993) argues that the student protests of 1968 engendered a widespread 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. Aversion toward commercial engagements with firms can be gleaned from disclosures of university-industry collaborations (or lack thereof). For instance, Monsanto's $23 million, 12-year research deal with Harvard University in 1974 was kept private until press attention forced Monsanto to reveal the terms of the 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 (affiliated with Harvard University) in 1981.[9]

Gradually, however, appreciation for use-inspired research and industry collaborations was rediscovered due to several factors. First, major government initiatives such as the "War on Cancer" (National Cancer Act of 1971) indicated that key societal goals could be achieved through scientific research. To support practical applications of 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 West German and Japanese manufacturing firms, arguably enhanced the value of using research as an input to economic growth. For instance, state governments in Georgia and North Carolina looked to universities for regional economic development by inducing colocation of research contracting firms. Later, other policies encouraged colocation of spin-offs based on technology developed in academia (Geiger 2004).

### *B. The Expansion of the Market for Technology and Smaller Firms*

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

Although start-up firms backed by venture capital (VC) had been around since the 1950s (e.g., in the laser industry for defense contracts), their rise to prominence in the American innovation ecosystem occurred only after the emergence of the semiconductor and biotechnology industries. Mowery and Rosenberg (1998) 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 those technologies. Aided by liberal licensing policies that resulted from this pressure, small firms such as Microsoft, Apple, Texas Instruments, and Fairchild Semiconductors rapidly developed improved iterations of the original products (Tilton 1971; Malerba 1985). 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 repurposed for civilian use. The role of firms such as Genentech, which successfully commercialized a university invention into mass-produced human insulin, was crucial in encouraging entry by private equity firms into the biotechnology sector, which lent capital to scientist inventors who specialized in monoclonal antibodies and DNA splicing (Pisano 2006).

Intellectual property (IP) rights were significantly strengthened (Jaffe and Lerner 2006; Guellec and de La Potterie 2007). At the national level, the Federal Courts Improvement Act of 1982 established the US 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 intellectual property protection for chip designs. Also, although 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 industrial processes to be patented (Arora et al. 2004, 61). Globally, the office of the US 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) into the Uruguay Round of 1995.

As a result, American corporations reported $67 billion of income from licensing industrial intellectual property in 2002 (table 1), and the supporting Internal Revenue Service (IRS) data show an annual growth of 11% from 1994 to 2004 for IP licensing revenues, which outpaced average GDP growth (3.42%) in the same period (Robbins 2009). The number of transferred patents as measured by reassignments between firms has also risen substantially from around 7,000 to more than 12,000 cases per year between 1987 and 2014.[10] 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

**Table 1**
US Distribution of Technology Licensing Receipts by Sector for 2002 and 2011 (in $ Billions)

| | | Technology Royalty and License Fee Income (2011) | | |
|---|---|---|---|---|
| Sector | Licensing of IP Protected as Industrial Property (2002) | Total | Tech and Ind Process | Software |
| Manufacturing | 59.5 | 25.7 | 24.8 | .9 |
| Wholesale, retail, transport | 1 | 49.6 | 49.4 | .3 |
| Information | 1.9 | 27.7 | 2.1 | 25.6 |
| Finance and insurance | .2 | 1.6 | 1.3 | .3 |
| Professional and business services | 3 | 4.5 | 2 | 2.5 |
| Other industries | 1 | 1.2 | 1.1 | .1 |
| Total | 66.6 | 111.2 | 81 | 30.2 |

Note: This table shows the distribution of technology licensing receipts in the United States. The figures for 2002 are from Robbins (2009) Table 4.10. The figures for 2011 are from the Census Enterprise Statistics Program 2011 Table 3: Royalty and License Fee Income from Rights to Use Intellectual Property (Detail). https://www.census.gov/econ/esp/historical.html.

research consulting firms such as Strategic Resources, Inc. (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).

### C. *The Decline of Corporate Research*

Another transformation of the American innovation ecosystem was the decline of the large corporate lab. This decline was 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, and grew to $100 billion and $82 billion in 1998. In 1979, GE's corporate research laboratory employed 1,649 doctorate holders while IBM employed 1,300. The comparable figures in 1998 were 475 doctorate holders for GE and 1,200 doctorate holders for IBM (National Research Council 1980, 1998). US public firms whose sales grew by 100% or more between 1980 and 1990 published 20.6 fewer scientific articles per year. This contrast between sales growth and publications drop persisted 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.[11]

A prominent example of corporate withdrawal from science is given by DuPont. The firm closed its Central Research & Development Organization and merged it with its engineering division in 2016. In the early and mid-twentieth century, the DuPont Central Research & Development Organization was 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 United States Patent and Trademark Office (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 Central Research lab ceased to operate as a research unit.

Aggregated data from the NSF show a similar pattern of corporate research decline, whereby the ratio of basic to applied research in corporate R&D declined from 50.7% in 1985 to 42.5% in 2015 (Boroush 2017, tables 3 and 4). Arora et al. (2018) disaggregate this trend further and find that, although a significant fraction of corporate publication decline can be attributed to entry by firms that publish very little, incumbents with established research programs also markedly decreased their research. The decline in publications is most evident in publications in high-impact scientific journals. The implied private value of scientific capability, as measured by stock market valuations or by the acquisition price in merger and acquisition (M&A) deals, also declined. By contrast, patenting by large American firms increased, and the implied private value of patents, including the premium paid for patents in M&A, increased.

We use corporate publications data from 1980 to 2015 to explore these trends in more detail. Our sample consists of all R&D performing public firms headquartered in the United States and 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 Index files. We also match these firm names to the assignee names for US utility patents available from EPO PATSTAT. Details on the matching process are available from Arora, Belenzon, and Sheer (2017).[12] The results in Arora et al. (2018) are summarized in figure 8, which graphs scientific publications and patents by Compustat firms with at least $10 million of

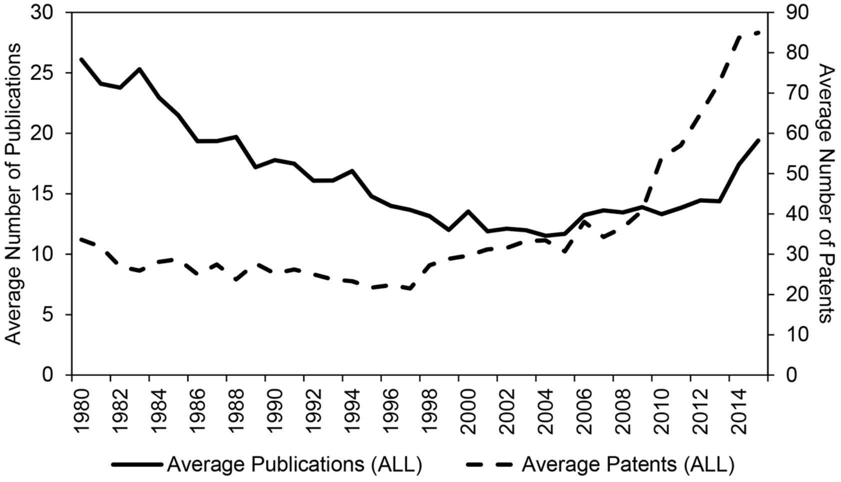

**Fig. 8.** Scientific publications and patents by Compustat firms (excluding life sciences)

Note: The solid lines represent the average number of publications in Clarivate Web of Science matched to Compustat firms with more than $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]).

R&D stock. Consistent with their finding, publications by firms decreased from around 25 to 15 between 1980 and 2015. In contrast, patenting by firms increased from around 10 to more than 70 patents per year in the same period. Among large US public firms with more than $100 million in R&D stock, 184 out of 201 firms (91.5%) published at least one scientific article in 1980. This number dropped to 73.6% in 2015 (528 firms out of 717 published). The decline is more pronounced for the most research-active firms: the ratio of firms that publish more than 10 articles per year dropped from 55.2% (111 out of 201 firms in 1980) to 29.8% (214 out of 717 firms in 2015). The average number of scientific publications per $1 million of R&D spending also declined from 0.46 article between 1980 and 1985 to 0.40 article between 2010 and 2015. The decline also seems to be more pronounced for older firms. For instance, there were 109 firms out of 131 (83.2%) listed on the stock market on or before 1980 that published in 2015. This ratio drops to 78.9% (15 out of 19) for firms listed in 1995 and 75.7% (28 out of 37) for firms listed in 2000.

Firms in the information technology (IT) sector did not buck this trend toward declining corporate publications. Figure 9 shows publications per $ thousand sales for Facebook, Amazon, Apple, Google, Microsoft, and Netflix. Firms in this group did publish more than other firms: in 2015, they published on average 304.7 articles, which is around 14 times

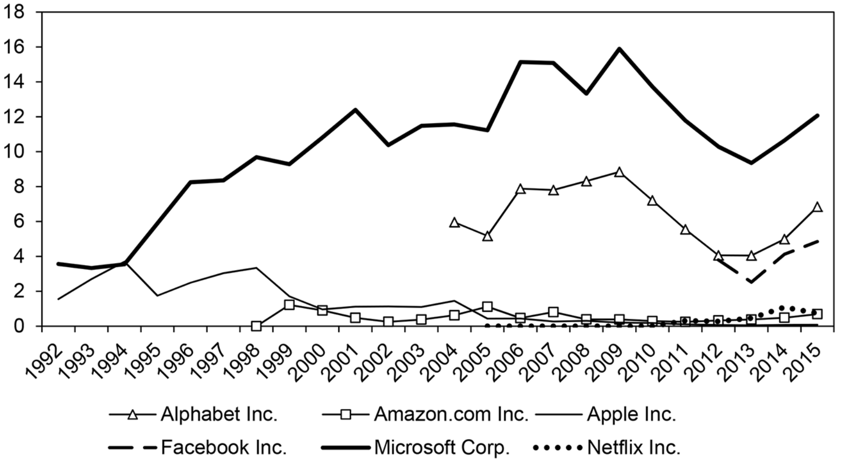

**Fig. 9.** Scientific publications per $ thousand sales for new IT sector firms

Note: This plot graphs the normalized number of scientific publications by large US firms in the IT sector. Scientific publications of Apple, Amazon, Facebook, Google, Microsoft, and Netflix found in Clarivate Web of Science are summed each year and divided by $ thousand sales. Details on matching procedure are found in Arora et al. (2017).

the average for all firms in that year (21.5 articles). However, Google and Microsoft are the dominant contributors to journals, together publishing close to 90% of all articles from these six firms. Moreover, except for Microsoft, publications normalized by sales fell over time between 1992 and 2015.

Of the 341 public firms publishing at least one scientific article in 1980, 223 (65.4%) saw a drop in publications in 1990. Similarly, 280 out of 470 firms (59.6%) publishing at least one scientific article in 1990 saw a drop in 2000. The comparable figure for the 2000–2010 period is even higher: 671 out of 902 (74.4%) firms publishing in 2000 produced fewer publications in 2010. To investigate this trend further, table 2 summarizes publication and patenting trends for the 10 firms that published the most scientific articles in the 1980s, 1990s, and 2000s. We explore how the publishing and patenting behavior of these firms changed in the following decade. As expected, firms such as GE, Xerox, and AT&T exhibited some of the sharpest declines. Table 2's "Top 10 publishers in 1980–89" section indicates that GE saw a drop of 132 articles between the 1980s and 1990s (from 603 to 471), while articles by Xerox declined from 343 to 310. Also, IBM's publishing trend in the 1990s (a 9% decline) contrasts with a near doubling in patenting in the same period. This result is consistent with the evidence presented by Bhaskarabhatla and Hegde (2014), which shows that IBM's pro–patent policies introduced by James McGroddy in 1989 incentivized researchers to patent rather than publish research results.

Table 2 also shows several anomalies to this overall pattern that deserve mention. First, the absolute number of publications declined sharply (by 73%) at AT&T from the 1990s to the 2000s, consistent with the firm's restructuring efforts. However, AT&T's R&D budget fell even more drastically, from $4,083 million in 1995 to $640 million in 1996, since it had spun off Bell Labs to Lucent Technologies. As a result, AT&T's papers normalized by R&D actually rose. Second, DuPont registered an increase in publications between the 1980s and 1990s. However, the growth promptly reversed in the following decade, where there is a drop of 339 articles, from 762 in the 1990s to 423 in the 2000s.

Third, firms in the life sciences such as Pharmacia, Lilly, Bristol Myers Squibb, and Pfizer significantly increased publications. In the case of Pfizer in the 2000s, this increase in publishing kept up with changes in R&D expenditures. One key feature of the pharmaceutical industry during this time period was strong merger activity. However, comparisons with other sectors that also experienced frequent mergers suggest that the

**Table 2**
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 | 1980–89 | 1990–99 | Change (%) | Change (%) (R&D Normalized) | 1980–89 | 1990–99 | Change (%) | Change (%) (R&D Normalized) |
| | 1980–89: | | | | | | | | |
| 1 | AT&T Corp. | 1,889 | 1,028 | −46 | −58 | 372 | 422 | 13 | −13 |
| 2 | International Business Machines Corp. | 1,612 | 1,929 | 20 | −16 | 538 | 1,495 | 178 | 96 |
| 3 | General Electric Co. | 603 | 471 | −22 | −43 | 908 | 876 | −4 | −29 |
| 4 | Du Pont (E I) de Nemours | 600 | 762 | 27 | −25 | 350 | 506 | 44 | −15 |
| 5 | Exxon Mobil Corp. | 554 | 401 | −28 | −23 | 252 | 245 | −3 | 3 |
| 6 | Xerox Corp. | 343 | 310 | −10 | −41 | 271 | 718 | 165 | 73 |
| 7 | Pharmacia & Upjohn Inc. | 336 | 532 | 58 | −52 | 101 | 56 | −45 | −83 |
| 8 | CBS Corp.-Old | 321 | 108 | −66 | −47 | 410 | 233 | −43 | −11 |
| 9 | Pharmacia Corp. | 302 | 383 | 27 | −43 | 146 | 173 | 18 | −47 |
| 10 | Rockwell Automation | 279 | 188 | −33 | −63 | 181 | 171 | −6 | −49 |
| | | 1990–99 | 2000–2009 | Change (%) | Change (%) (R&D Normalized) | 1990–99 | 2000–2009 | Change (%) | Change (%) (R&D Normalized) |
| | 1990–99: | | | | | | | | |
| 1 | International Business Machines Corp. | 1,929 | 1,754 | −9 | −21 | 1,495 | 3,522 | 136 | 104 |
| 2 | Lucent Technologies Inc. | 1,421 | 748 | −47 | −9 | 799 | 770 | −4 | 66 |
| 3 | AT&T Corp. | 1,028 | 279 | −73 | 119 | 422 | 288 | −32 | 450 |
| 4 | Du Pont (E I) de Nemours | 762 | 423 | −44 | −31 | 506 | 475 | −6 | 17 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 5 | Bristol-Myers Squibb Co. | 582 | 632 | 9 | −56 | 135 | 158 | 17 | −53 |
| 6 | Schering-Plough | 565 | 557 | −1 | −71 | 99 | 111 | 11 | −67 |
| 7 | Pharmacia & Upjohn Inc. | 532 | Merged with Pfizer (2003) | N/A | N/A | 56 | Merged with Pfizer (2003) | N/A | N/A |
| 8 | Eli Lilly and Co. | 508 | 884 | 74 | −44 | 138 | 97 | −30 | −78 |
| 9 | Abbott Laboratories | 474 | 600 | 26 | −48 | 138 | 128 | −7 | −62 |
| 10 | General Electric Co. | 471 | 762 | 62 | −11 | 876 | 1,269 | 45 | −20 |

| | | 2000–2009 | 2010–15 | Change (%) | Change (%) (R&D Normalized) | 2000–2009 | 2010–15 | Change (%) | Change (%) (R&D Normalized) |
|---|---|---|---|---|---|---|---|---|---|
| | 2000–2009: | | | | | | | | |
| 1 | International Business Machines Corp. | 1,754 | 1,703 | −3 | −11 | 3,522 | 6,800 | 93 | 76 |
| 2 | Pfizer Inc. | 1,616 | 2,022 | 25 | 19 | 318 | 167 | −47 | −50 |
| 3 | Johnson & Johnson | 1,014 | 1,382 | 36 | −3 | 378 | 781 | 106 | 47 |
| 4 | Eli Lilly and Co. | 884 | 868 | −2 | −33 | 97 | 70 | −28 | −51 |
| 5 | General Electric Co. | 762 | 997 | 31 | −23 | 1,269 | 1,945 | 53 | −10 |
| 6 | Lucent Technologies Inc. | 748 | Merged with Alcatel (2006) | N/A | N/A | 770 | Merged with Alcatel (2006) | N/A | N/A |
| 7 | Merck & Co. | 648 | 866 | 34 | −36 | 307 | 541 | 76 | −16 |
| 8 | Bristol-Myers Squibb Co. | 632 | 844 | 34 | −4 | 158 | 172 | 9 | −21 |
| 9 | Intel Corp. | 625 | 702 | 12 | −44 | 1,463 | 1,793 | 23 | −39 |
| 10 | Abbott Laboratories | 600 | 568 | −5 | −23 | 128 | 532 | 316 | 240 |

Note: This table describes annual patenting and publication activities of Compustat firms that are the top publishers for each decade from 1980 to 2015 (1980–89, 1990–99, 2000–2009, and 2010–15). We divide the total number of publications by number of years in every decade for US-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 (fifth column). We also divide the number of publications each year by $ million R&D spending and average over each decade for each firm. The percentage difference between each decade in this measure is presented in the sixth column. The same is done for patents from the seventh to tenth columns.

publishing behavior of firms in the life sciences was not simply an artifact of such activity. Figure 10 plots the ratio between the number of scientific publications per firm and patents per firm by main industrial sector. The figure shows that, in the life sciences, this ratio grew from close to one in the 1980s to between three and five in more recent years. By contrast, publications to patent ratios for both the computer/IT/software and electronics/semiconductor sectors more than halved over the same period.

Apart from the rise in average firm size, there are several other plausible reasons why the pharmaceutical and biotech sector bucked the trend toward declining scientific publications. First, the commercial applicability of upstream research, such as that conducted in universities or published in scientific journals, is much more apparent in the life sciences than in other manufacturing sectors. For example, in the mid-1990s, 58% of industrial R&D lab managers in the pharmaceutical sector

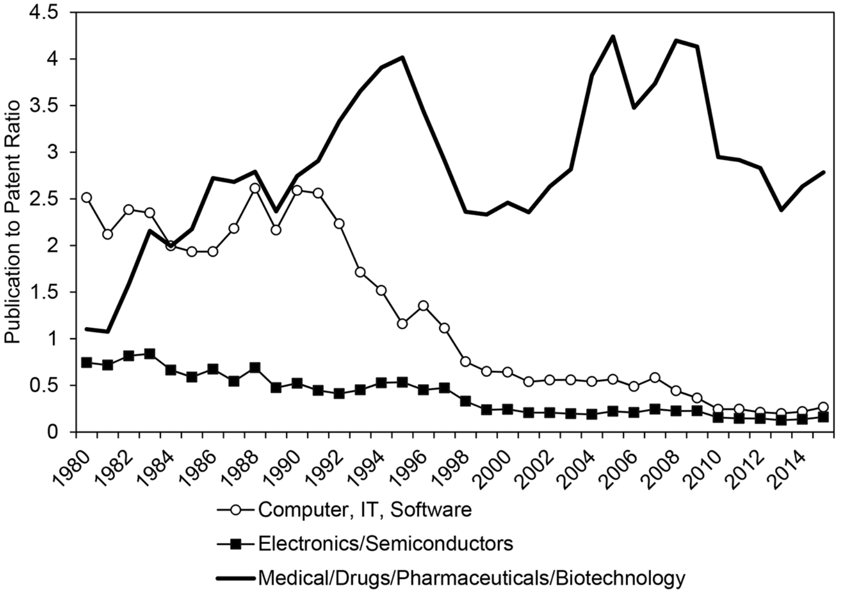

**Fig. 10.** Ratio of publications per firm to patents per firm, by industry

Note: This graph plots the ratio of publications to patents per firm in three industrial sectors. The number of publications per firm is calculated by matching publications in Clarivate Web of Science to Compustat firms with more than $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.

reported that research conducted in academic or government labs suggested new project ideas, well above the manufacturing average of 32% (Cohen, Nelson, and Walsh 2002). Second, patents are generally viewed as more effective in protecting the sale and commercialization of knowledge in the drug industry than in other sectors. Relatedly, technology markets are very active in pharmaceuticals. As a result, returns to investments in research may be higher in the life sciences than in other sectors. In particular, large pharmaceutical companies may have to carry out some research in-house to be competent buyers of technology. Third, drugs require regulatory approval, and scientific publications, by demonstrating the efficacy of new products, can facilitate this process. 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, for instance, scientific publications (Hicks 1995; Azoulay 2002).

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 11 shows that this steep

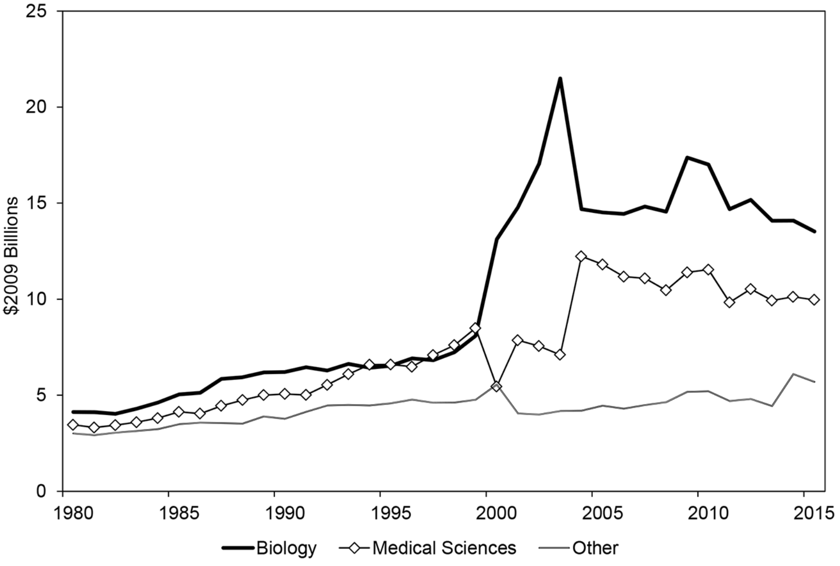

**Fig. 11.** Federal obligations by selected subfields, FY 1980–FY 2015

Notes: This graph replicates figure 4 in 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. Other includes chemicals, computer sciences, materials engineering, metallurgy, and electrical engineering.

increase in federal funding for life sciences has not been matched in other sectors such as chemistry, computer sciences, materials, and electrical engineering. This plausibly increased publication output by firms, not only those that made use of NIH funds, but also those that could freely access newly available public resources such as genome sequences to increase research productivity. However, this confluence of factors was unique to the life sciences, which may explain why it has stood out among other sectors.

In summary, 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 more than 6,000 manufacturing- and service-sector firms in the United States, Arora, Cohen, and Walsh (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 therefore invest in scientific capability not so much to generate knowledge as to be effective buyers of knowledge.

### *D. Why Has Corporate Science Declined?*

The withdrawal from science by large corporations resulted from the confluence of several factors. As competition intensified and the interval between invention and commercialization narrowed, it became increasingly difficult for corporations to profit from their in-house research. Standard theory implies that firms reduce research when the knowledge spills out, particularly to rivals. This intuition is supported by the results in Arora et al. (2017) who further document that spillovers to rivals have greatly increased between 1980 and 2015.[13] As former Bell Labs researcher Andrew Odlyzko 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. (Odlyzko 1995, 4)

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) 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" (302). Thus, as firms concentrated on their core markets, their incentives to invest in scientific research may have declined. Trade, outsourcing, and the offshoring of manufacturing may also have reduced the incentives to invest in research. For instance, moving manufacturing to locations far from where R&D takes place could reduce interactions between research and production, which may hinder innovation.

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 antitrust pressures, and with little on offer from universities and independent inventors, it often 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.

The growth of university research likely also contributed to the ease of external knowledge acquisition. Corporate labs 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 earlier, however, over time universities and small firms became 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 also increased. 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 so.

## V. 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 rise and fall of American productivity 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. Although 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. Although large corporations are withdrawing from internal research because it is no longer privately profitable, this change may not be positive for society.

### *A. 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.

#### 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 toward systemic innovations (which require extensive coordination and communication across different stages of production and actors) and less toward 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 supports 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, nonequilibrium superconductivity, and ballistic electron motions because it saw an opportunity to preempt the next revolutionary chip design in its industry (Gomory 1985; Rosenberg 1994, 258). Finally, a recent surge in corporate publications in machine learning (ML) 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, forthcoming).

### Corporate Labs Solve Practical Problems

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 pathbreaking 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 toward the most applied end of the spectrum and have only limited scientific value. 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."[14]

### Corporate Labs Are Multidisciplinary 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 firsthand 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 1 part in 10 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 in 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.

Artificial intelligence (AI) research is an example that shows the difference between large corporate lab research from universities and start-up research. Since the beginning of this decade, large corporations such as Google, IBM, and Facebook have invested heavily in AI research. Hartmann and Hankel's (forthcoming) recent study shows that the share of corporate publications in top AI journals, such as the International Conference on Machine Learning (ICML), has tripled between 2004 and 2016.

Firms have pioneered research in specialized fields such as deep neural networks (DNNs). Google has published landmark papers, such as the "Cat Paper" (Le et al. 2011) and the "Google Translate Paper" (Wu et al. 2016), which validate the effectiveness of new algorithms such as LSTM (Long-Short Term Memory) for image recognition and language translation, respectively. Although many scientists working at Google for these projects (such as Andrew Ng at Stanford and Geoffrey Hinton at Toronto) had joint appointments at universities, it is unlikely that either universities or VC-backed start-ups would have produced research output on par with Google for three reasons.[15]

*Scale.* In 2018, Google employed more than 1,700 AI researchers and made a string of start-up acquisitions specializing in the field, starting with Geoffrey Hinton's firm (DNN research) in 2013 and following with Demis Hassabis's Deep Mind in 2014. Large firms such as Google also collect and maintain proprietary data sets that dwarf the sizes of publicly available ones collected at universities. In the field of machine learning, larger data sets allow for the empirical validation of algorithms that are difficult to solve analytically, which implies that the cutting-edge empirical work in AI necessarily occurs in firms, where the data are available. Sun et al. (2017) show that Google uses the JFT-300M data set that has more than 375 million labels for 300 million images (Stanford's Imagenet data set, one of the largest data sets made publicly available by a university, contained around 1 million images) and empirically show that increases in data size correspond to significant performance improvements. This result was intuitively plausible but difficult to test at scale.

*Multidisciplinarity.* Researching neural networks requires an interdisciplinary team. Domain specialists (e.g., linguists in the case of machine translation) define the problem to be solved and assess performance; statisticians design the algorithms and theorize on their error bounds and optimization routines; computer scientists search for efficiency gains in implementing the algorithms. Not surprisingly, the "Google Translate Paper" has 31 coauthors, many of them leading researchers in their respective fields (Wu et al. 2016). This seems to be a broader trend separating university research from industry research in this area: using data from Marx and Fuegi (2019), we examined the average number of coauthors in the five leading ML conferences in Hartmann and Henkel (forthcoming) from 2011 to 2018 and found that research by large firms features on average one more coauthor (4.3) than papers by smaller firms (3.4).[16] These firms make up 10% (2,168 out of 20,989) of the papers published with fewer than 11 authors but comprise 28%

(22 out of 79) of the papers published with more than 11 authors. High-quality papers show the same difference in the size of teams. Among ML conference papers in the top decile by citations received, corporate publications involve 4.4 authors, whereas non-firm publications involve 3.6 authors. This pattern holds for the top 1% of cited publications.

*Complementary equipment.* The collaboration between science and engineering is also an advantage at Google Brain that is hard to replicate in universities or VC-backed start-ups. To implement code written by Quoc Le (one of the leading scientists on the Google Translate project), software engineers converted Le's code into Google's newly developing Tensor Flow language, while hardware engineers debugged Google's proprietary tensor processing units (TPUs) that were custom-built by Google for inference tasks in neural networks.[17] Google has continuously improved on these chips, with four generations of TPU chips being introduced in the span of two years. A few universities such as MIT (Eyeriss), Georgia Tech, ETH Zurich (Nullhop), and IIT Madras are conducting research on such "AI-accelerator" chips, but their products are yet to be fielded widely on the market.

A consequence of large corporate research being (a) general purpose, (b) closely coupled with practical problems, and (c) multidisciplinary is that, on average, corporate scientific research will be more useful to inventors than university research. If so, then we should observe inventors of patents, for instance, devote more attention to corporate research than to its academic counterparts.

Anecdotal evidence suggests that neural network research published by Google Brain has been implemented by follow-on research at firms. It is now standard practice among researchers to test their algorithm's performance against Alexnet or LSTM, both of which were refined at Google. We find that ML papers published by large firms are cited more often in patents than other ML papers: large firms published 12% of the papers in knowledge discovery in databases (KDD), Association for the Advancement of Artificial Intelligence (AAAI), International Conference on Machine Learning (ICML), International Joint Conference on Artificial Intelligence (IJCAI), and Neural Information Processing Systems (NIPS) between 2011 and 2018 but accounted for 32% of the papers that are cited by patents.

Bikard (2015) finds corporate publications to be 23% more likely to be cited than university publications on the same scientific discovery. We add wider correlational evidence in support of this prediction by comparing the likelihood of a US utility patent issued between 1980 and

2006 citing a corporate scientific publication versus a university counterpart in its non–patent literature section. Using a linear probability model, we estimate that corporate publications are on average 11% more likely to be cited than 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 12 visualizes the citation likelihood differences between these two groups whereas panel (B) shows that corporate publications first-order stochastically dominate university publications in terms of the number of citations they receive from patents.

### Large Corporate Labs May Generate Significant External Benefits

Besides 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 personal computer (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. Although 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.

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 US innovation ecosystem. He found that in many high-tech industries, including the early automobile industry, semiconductors, and lasers, spin-offs were exceptional performers. 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

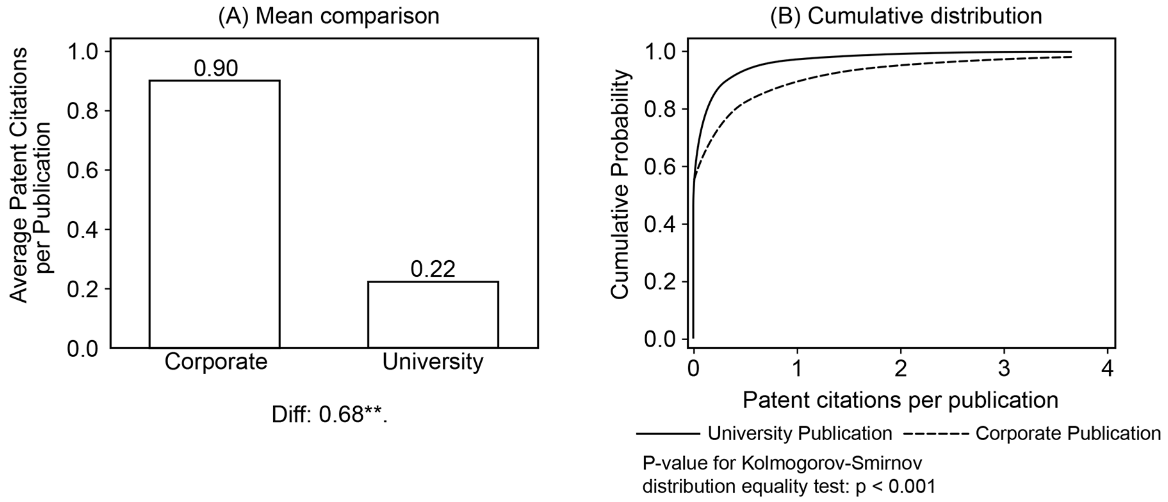

**Fig. 12.** Patent citation to university vs. corporate publications

Note: The sample includes publications from the top 100 US 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 are measured by total citations (internal and external) per publication by corporate and noncorporate patents granted between 1980 and 2014. Panel A presents mean comparison for university versus corporate publications by patent citation received per publication. Panel 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).

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.

## VI. The Policy Environment

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

### *A. Antitrust*

As noted in Sections II and III, 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 US 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 US patents) became freely available. Most of these patents covered technologies that had been developed by Bell Labs, the research subsidiary of the Bell System.[18]

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% with an effect that 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 for Bell's reduced incentives to innovate. In an in-depth case study, Watzinger et al. (2017) demonstrate that the decree accelerated the diffusion of transistor technology, one of the most important technologies of the twentieth century.

This view that the consent decree was decisive for US post–World War II innovation, particularly by spurring the creation of whole industries, is shared by many observers. As Gordon Moore, the cofounder 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, 86 as quoted in Watzinger et al. 2017).

Scholars such as Peter Grindley and David Teece (1997, 258) 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" (as quoted in Watzinger et al. 2017).

Starting in 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.

### *B. Bayh-Dole and University Research*

There is a slew of policy inducements to research, development, and commercialization. Here, we focus on one that relates to commercialization of university research: the Bayh-Dole Act. Dubbed "[P]ossibly the most inspired piece of legislation to be enacted in America" by *The Economist*, the act was enacted by Congress in 1980 with the goal of facilitating the commercialization of university science.[19] The law eliminated US government claims to university-based innovation, giving US universities the rights to inventions that were federally funded. Although we remain agnostic on the extent of inspiration (or lack thereof) behind 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 US 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 data set than previously available, Ouellette and Tutt (forthcoming) 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 institutions 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 has 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 in which university researchers had full ownership of their inventions (the "professor's privilege") to a system where inventors, just like in the United States today, only hold 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% drop 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 with controls. Overall, the reform, by reducing researchers' ownership stakes, appears to have discouraged university innovation.

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 start-ups and university spin-offs being responsible for developing university inventions, relying upon private investors or venture capital for support. In so doing, not only the rate of technical advance but also its direction is affected.

### *C. Mission-Oriented Agencies*

Corporate labs play an important role in the US 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) defines mission-oriented policies "as systemic public policies that draw on frontier knowledge to attain specific goals" (804). 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 United States (Mowery 1997; Sampat 2012). For instance, in 2008 the NIH alone was responsible for funding nearly 30% of all US 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."[20] Azoulay et al. (2019) 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" (88). ARPA-ble research is distinct from basic research because it is mission-oriented and also different from pure applied research in that its focus is not on incremental advances but on "transformational change." ARPA-funded projects may involve advancing the scientific frontier, but this is incidental to the main goal of making 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 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 to large defense contractors (Mazzucato 2015). Military procurement more broadly played a key role in spurring spin-off and start-up 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 US 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." In conclusion, 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" (Mazzucato 2015, 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 likely contributed to US life science companies not withdrawing from scientific research, unlike firms in other sectors.[21]

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 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.

## VII. 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 with 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 antitrust 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 them 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 in that it is less likely to be mission driven. Its smaller scale and greater disciplinary focus mean that university research typically produces insights that then need further development and integration to produce inventions that can be commercialized. 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. 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.

## Endnotes

For acknowledgments, sources of research support, and disclosure of the authors' material financial relationships, if any, please see https://www.nber.org/chapters/c14259.ack.

1. Indeed, Bloom et al. (2017) present evidence across a number of sectors showing that research productivity in the United States has declined since the 1970s. 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. Although growth rates for yields per acre for corn, 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), a research productivity decline of about 4–6% 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.

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

3. According to personal communications with Ralph Gomory (former research director and senior vice president for science and technology at IBM), IBM even downplayed to investors the discovery of the scanning tunneling microscope (which earned Gerd Binnig and Heinrich Rohrer of the IBM Zurich Research Laboratory the Nobel Prize in physics in 1986), for fear of a drop in share price.

4. https://cen.acs.org/articles/94/i1/DuPont-Shutting-Central-Research.html.

5. Arora et al. (2017) show that companies remain engaged in research when they can use the research in internal inventions and can restrict spillovers to product-market rivals.

6. In absolute terms, the number of patents assigned more than doubled over this period, but the number of patents granted grew even faster.

7. Industry executives took a keen interest in the world of science as well. AT&T Bell Labs president Frank Jewett was instrumental in persuading Princeton physicist Karl Compton to take up his presidency at MIT and later served as president of the National Academy of Sciences from 1939 to 1947.

8. Sponsored industrial research at MIT exceeded $100,000 in 1920–21 and rose to more than $270,000 by 1930 (Geiger 1986, 179).

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

10. Authors' calculations are based on data from the USPTO Patent Assignment Dataset (Graham et al. 2018), replicating cleaning procedures in (Serrano 2010) identifying patent reassignments that qualify as market transactions.

11. Calculations based on authors' data on Compustat firms matched to Clarivate Web of Science and EPO PATSTAT. Details are found in Arora et al. (2017).

12. We thank Honggi Lee, Lia Sheer, and Dror Shvadron for their excellent assistance on constructing the data set.

13. Spillovers in this study are measured by citations to corporate publications received from patents filed by rivals.

14. Letter to the *Wall Street Journal*, available at http://www.dtc.umn.edu/odlyzko/misc/wsj-bell-labs-20120326; accessed February 18, 2019.

15. Hinton (a co-laureate of the Turing Award in 2018 with Facebook's Yann LeCunn and McGill's Yoshua Bengio) was a pioneer of neural networks and supervised the execution of Alexnet, the first algorithm to bring error rate in the Imagenet competition down to under 25% in 2012.

16. The five conferences are Knowledge Discovery and Data Mining (KDD), the Association for the Advancement of Artificial Intelligence (AAAI), the International Conference on Machine Learning (ICML), the International Joint Conferences on Artificial Intelligence (IJCAI), and the Conference on Neural Information Processing Systems (NIPS). The "large firms" are Microsoft, Google, IBM, Yahoo, Toyota, Baidu, NEC Corporation, Facebook, Adobe, and LinkedIn and rank as the top publishers in the field of AI in Hartmann and Henkel (forthcoming).

17. TPUs are custom application specific integrated circuits (ASIC) specifically designed for deep neural networks. The first TPUs were deployed in Google data centers in 2015 and performed up to 26 times faster than existing graphics processing units.

https://cloud.google.com/blog/products/gcp/an-in-depth-look-at-googles-first-tensor-processing-unit-tpu.

18. Moser and Voena (2012) also find that compulsory licensing spurs innovation. They examine compulsory licensing after World War I under the Trading with the Enemy Act to identify the effects of compulsory licensing on domestic (US) invention. Their analysis of nearly 130,000 chemical inventions suggests that compulsory licensing increased domestic invention by 20%.

19. https://www.economist.com/technology-quarterly/2002/12/12/innovations-golden-goose.

20. https://www.darpa.mil/about-us/mission.

21. 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.

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