Righting the Research Imbalance

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Abstract: Research (basic and applied) in the physical sciences and engineering (PS&E) has yielded concepts and results important to technological innovation, economic growth, and national security and will continue to do so in the future. Since the end of the cold war, however, public funding of research in these fields has lagged in relation to the size of the economy, comparable expenditures by governments of other advanced and advancing countries, and our own government's support of the biological and medical sciences. Until now, congressional and administration efforts over the past decade to reverse this decline have largely failed. Research support from other sources—businesses, philanthropies, and other nonprofit institutions including universities themselves—is similarly focused heavily on the life sciences; and there is evidence of declining spillovers from industry-sponsored research, more so in information technology-related fields than in biopharma.

Enacting coordinated increases in funding across the several federal government agencies supporting PS&E research has faced high hurdles, in part because of statutory caps on discretionary spending, in part because of the multiplicity of responsible congressional committees. A February 2018 budget agreement raised the limits on nondefense spending by 12 percent and defense spending by 14 percent, paving the way for the FY 2018 Consolidated Omnibus Appropriations Act to provide significant increases in research spending across most agencies and research fields. This is an important first step in addressing the PS&E research deficit; but unless other action is taken, the spending caps will be reinstated in 18 months. Moreover, a centrally coordinated effort is needed to ensure productive use of the sudden infusion of resources.

Introduction

In January 2018, the release of a normally dry government statistical compilation rang alarm bells on both sides of the aisle on Capitol Hill. Referring to the National Science Board's latest *Science and Engineering Indicators* (National Science Board, 2018) report, Senator Cory Gardner (R-CO) observed that although the United States continues to lead the world in research and developing spending, with 28 percent the global total in 2015, China with 21 percent is a close second. "Unless we dedicate more support to our nation's R&D enterprise, we will lose out to competitors like China who are working to displace (us) as the world's greatest innovator." And Senator Bill Nelson (D-FL) found it "chilling" that China's R&D investment has been growing by 18 percent annually since 2000 while US spending is increasing at only 4 percent. "At this rate China may soon eclipse the U.S., and we will lose the competitive advantage that has made us the most powerful economy in the world" (American Institute of Physics, 2018).

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[*] This paper derives from presentations by Duke investigators at a Washington, DC, conference, "The Decline in Corporate Research: Should We Worry?" organized by The Center for Innovation Policy at Duke Law, March 31, 2017 (available at https://law.duke.edu/innovationpolicy/changing-innovation/). The findings were also the subject of a Capitol Hill briefing on June 6, 2017. The author acknowledges the support of the Ewing Marion Kauffman Foundation and the Duke Office of the Vice Provost for Research.

R&D is unquestionably an engine of growth and source of comparative advantage. When in the last decade the Commerce Department's Bureau of Economic Analysis (BEA) began treating R&D as an investment with future returns rather than a current year expense of government and business, it found that public and private spending together accounted for 7 percent of the annual growth in overall GDP between 1995 and 2007. Seven percent may seem like a small number, but it is two-and-a-half times the share of R&D spending in U.S. GDP (2.7 percent) (Okubo and Moylan, 2017). And although one might suspect that industry-funded R&D contributes more to the economy than government-funded R&D, that appears not to be the case. The latter's contribution to growth is comparable to its share of total U.S. R&D investment despite the fact that private spending is heavily weighted toward "D," development, defined by the National Science Foundation (NSF) as the "use of knowledge for the production of useful materials, devices, systems, or methods including the development and testing of prototypes," whereas public spending, apart from the military's, has traditionally been oriented toward "R," investigation to "gain knowledge of fundamental aspects of phenomena or determine how a recognized need can be met"—in other words, towards activities well upstream of commercial products and services.

The amount of R&D activity matters but so does its composition. "Composition" can refer to different stages of R&D (as defined above), different funders, different performers, or different fields and industry sectors. This paper focuses on the research end of the R&D spectrum and addresses how public policy affects the distribution of research effort by subject area. It argues that policies such as taxes and intellectual property are generic instruments that have some influence on the amount of private R&D spending but little near term effect on its distribution across industries, technologies, or stages of R&D.

The main policy instrument affecting the field composition of research is, of course, direct federal government spending. And here there have been two concerns. The first is the overall level of effort which has been falling in relation to the size of the U.S. economy, not to mention in relation to the government expenditures of other countries with advanced or emerging economies. President Trump's proposed FY 2018 and FY 2019 budget requests would have further reduced it. But this is a widely recognized issue, and Congress has squarely addressed it by turning down most of the cuts and opening the door to funding increases in the remainder of FY 2018 and FY 2019 by lifting the budget caps on defense and domestic spending.

A second serious concern, recognized a decade ago but not effectively addressed to date, is the growing imbalance in the federal government's research portfolio. Since the end of the Cold War that portfolio has shifted dramatically—away from the physical sciences and engineering (PS&E) and toward the life sciences. Most PS&E fields have received only marginal increases in funding since the 1980s and some have seen reductions in real terms. Moreover, recent research described below suggests that this neglect may be exacerbated by developments in the private sector.

Why is the PS&E deficit a concern? In the Senators' view, the principal reason is the rise of Chinese economic and strategic competition focused in part on science and engineering. Chinese R&D policy has been the subject of several recent congressional hearings in the armed services as well as civilian science funding committees. These have highlighted China's priority investments, articulated in the current five-year strategic plan emphasizing innovation as the primary engine not only for economic growth but also military advantage—PS&E fields such as quantum computing, artificial intelligence, robotics, and autonomous vehicle and space technology. It has been noted that other countries and regions, particularly the European Union and Canada, are also increasing their investments in these same fields. The Chinese and others are also promoting biomedical research but it is not usually seen as an arena in which the United States faces the strongest competition.

From a domestic economic perspective, the role of R&D in the physical sciences and engineering is also compelling. The BEA estimates of private R&D contributions to economic growth in the period 1995–2007[1] break down as follows (Figure 1).

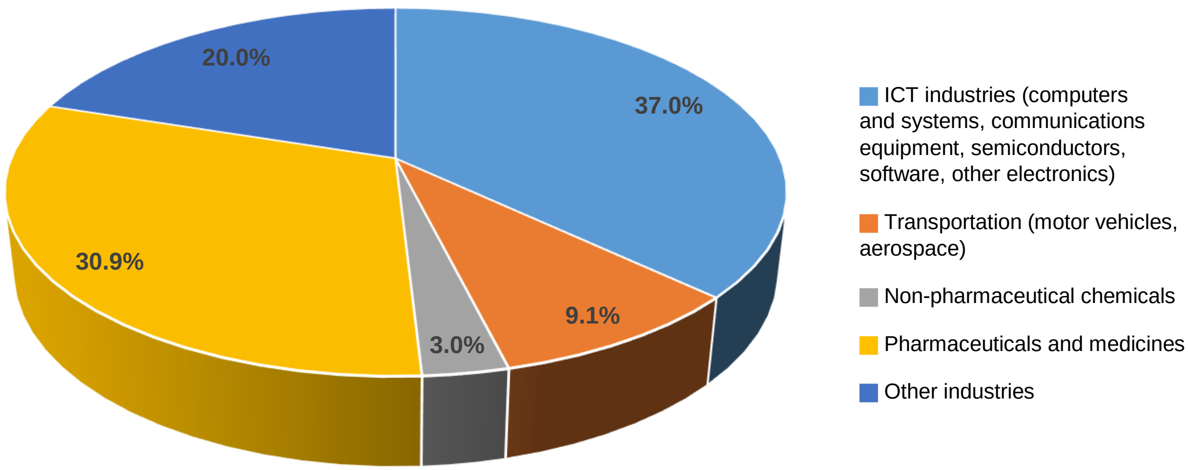

Figure 1: Private R&D Contributions to Economic Growth, 1995–2007

Source: Bureau of Economic Analysis, U.S. Department of Commerce.

Together, the PS&E-reliant sectors of the economy account for at least 50 percent of the entire contribution of private R&D to growth.

Another way of thinking about the role of PS&E research in the economy is to consider a sector that is entirely the product of public and private R&D in those fields, the so-called digital economy. In fact, the three building blocks of the digital economy—the semiconductor chip, the Internet, and GPS—owe their existence in large part to the federal government. BEA's recent report, *Defining and Measuring the Digital Economy* (Barefoot, Curtis, Jolliff, Nicholson, and Omohundro, 2018), considers only the goods and services that are "primarily," not "partially," digital—the computer, software, and telecommunications infrastructure; e-commerce, and digital media. Thus narrowly defined, the digital economy in 2016 represented 6.5 percent of national GDP ($1.2 trillion), larger than wholesale and retail trade, construction, transportation, utilities, mining, and agriculture. It supported 5.9 million jobs and was growing at nearly four times the national growth rate—a "bright spot" in the economy, to use BEA's understatement.

The remainder of this paper considers five questions:

- What is the evidence underlying the assertion that there is an imbalance in federal funding?
- How did it come about?
- What happened to attempts to correct it?
- Have non-federal government sources of funding stepped up to compensate?
- Do the FY 2018 appropriations solve the problem? If not, what further steps should be taken?

[1] In the BEA estimates, the private sector R&D contribution to growth is not disaggregated by stage of R&D nor is the public sector's R&D contribution by field. A further limitation of the BEA data series is that for the time being it is not possible to extend the estimates beyond 2007. When BEA formally incorporated its treatment of R&D as investment into the national economic accounts in 2013 and ceased to produce a satellite R&D account, it was decided to fold software R&D into software production, eliminating a separate estimate of software R&D's contribution to growth. In 2007, software represented nearly 10 percent of the entire private sector R&D contribution to growth and the largest component of the ICT's contribution. In a comprehensive update to be issued in mid-2018, BEA will again separate software R&D from software production, enabling an estimate of total R&D's contribution to growth stretching from the late 1980s to the present.

Major Research Fields' Funding, 1980–2015

NSF survey data[2] enable us to construct a long term picture of which scientific research fields have prospered and which have not with changes in government agency budgets as well as support from non-federal sources. Each year agency officials are asked to report where the money went in terms of three broad fields of research (life sciences, physical sciences, and engineering) and twenty-two[3] sub-fields as well as to distinguish between research and development and between basic and applied work. University officials are asked to report very similar data on funding from all major sources—the federal government, states and localities, philanthropy and other non-governmental organizations, and institutions' own funds.

First, we look at federal government agencies' spending on research (basic and applied) across the three broad fields, extend the timeline back to 1980, before the end of the Cold War, and remove inflation by standardizing the dollars to a single year, 2009. Spending on engineering nearly doubled between 1980 and 2016, from $6.51 billion to $11.49, but spending on the physical sciences barely increased over the period, from $4.6 billion to $5.8 billion. Meanwhile, life science spending increased three times, from $9.63 billion to $28.58 billion, which was actually down from a peak of $33.61 billion in FY 2010 (Figure 2).

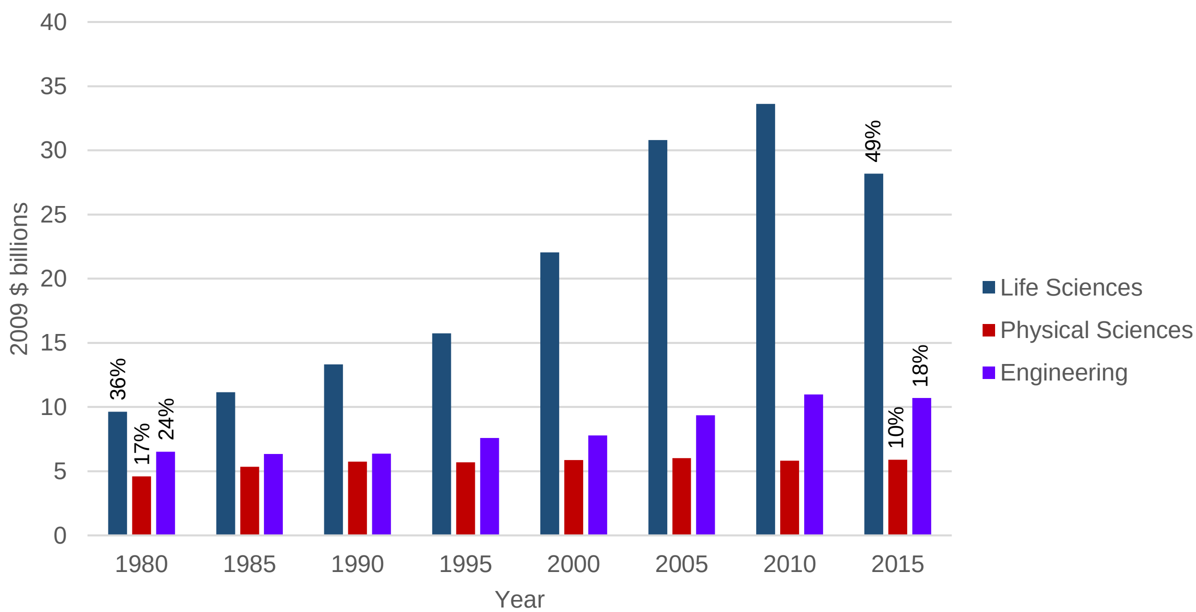

Figure 2: Federal Research Obligations by Major Fields, FY 1980–FY 2015

Source: NSF Federal Funds Survey.

[2] Data in this paper are drawn from surveys of R&D spending—primarily an annual survey of spending by research field by federal agencies (Federal Funds Survey) and an annual survey of research spending in universities and colleges (Higher Education Research and Development Survey). Reference is also made to the Foundation's BRDIS (Business Research and Development and Innovation) Survey of U.S.-based corporations. All three surveys distinguish among basic research, applied research, and development as defined above. For the most part this paper refers to "research" spending—a combination of basic and applied research—for the simple reason that both respondents to the surveys and users of the data are likely to have a clearer understanding of the differences between "research" and "development" than between "basic research" and "applied research." However, because the current Administration has described "basic science" support as the proper role of the federal government and questioned the appropriateness of public investment in some applied work as well as development, we also analyze trends in basic research funding.

[3] The number of sub-fields has varied slightly from survey to survey but has remained fairly stable over time. There has been much hand-wringing over whether the classification adequately captures changes in science, particularly the growth of cross-disciplinary research, but little consensus regarding major changes which could undermine longitudinal analysis.

Basic research spending across the three broad fields followed a similar pattern. Life sciences increased from $4.72 billion to $14.86 billion (again a drop from $17.59 billion in FY 2010), physical sciences from $2.81 billion to $4.28 billion, and engineering from $1.07 billion to $3.29 billion (Figure 3). The shift in the overall portfolio was substantial. In 1980 PS&E research represented 41 percent of the federal science budget. Thirty-five years later its share had fallen to 28 percent. The life sciences had picked up the entire difference. (The percentages do not add to 100 percent because other fields are omitted.)

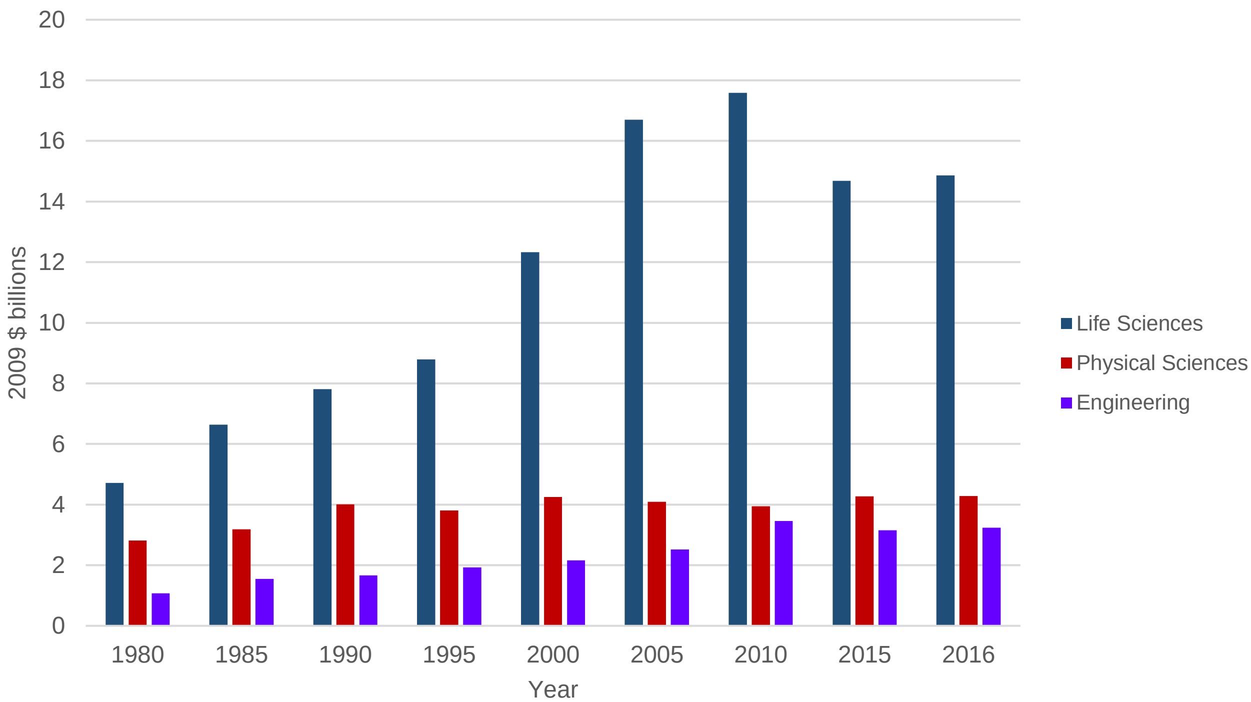

Figure 3: Federal Basic Research Obligations in Broad Fields, FY 1980–FY 2014.

Funding of Sub-fields with Industrial Applications, 1980–2015

For a finer-grain picture of trends over this period, we look at the most "commercially relevant" sub-fields of research. The following selection of fields is not subjective. In 1994, as part of a broad examination of the nature and determinants of industrial R&D, Wes Cohen, Richard Nelson, and John Walsh surveyed 1,500 R&D executives in manufacturing companies across the United States (Cohen, Nelson, and Walsh, 2002). Among the questions they asked: What fields of research did the managers access through publications, conferences, consultants and new hires and rely upon in their own work? Across diverse industries the most frequently cited fields were:

- Materials science and engineering[4]
- Computer science and electrical engineering
- Chemistry and chemical engineering
- Biological and medical science

[4] The authors found materials science to have "the most pervasive direct impact on industrial R&D" across half of 33 manufacturing industries spanning chemicals, metals, electronics, machinery, and transportation equipment, making it the closest thing to a "general purpose" research field (Cohen, Nelson, and Walsh, 2002, 12).

Of course, the economy has changed in twenty-plus years and unfortunately the survey has not been repeated, but the results are better than guesswork as to the commercial relevance of subfields of science and engineering research, at least in the manufacturing sector.

Here is what has happened over the period 1980 to 2015 to federal support of basic and applied research in these subfields (Figure 4):

- Both biological science and medical science support has tripled in real terms.
- Computer science and materials science and engineering support has also increased but from a very small base.
- Support of chemistry and electrical engineering has actually declined—by eleven percent and four percent respectively.

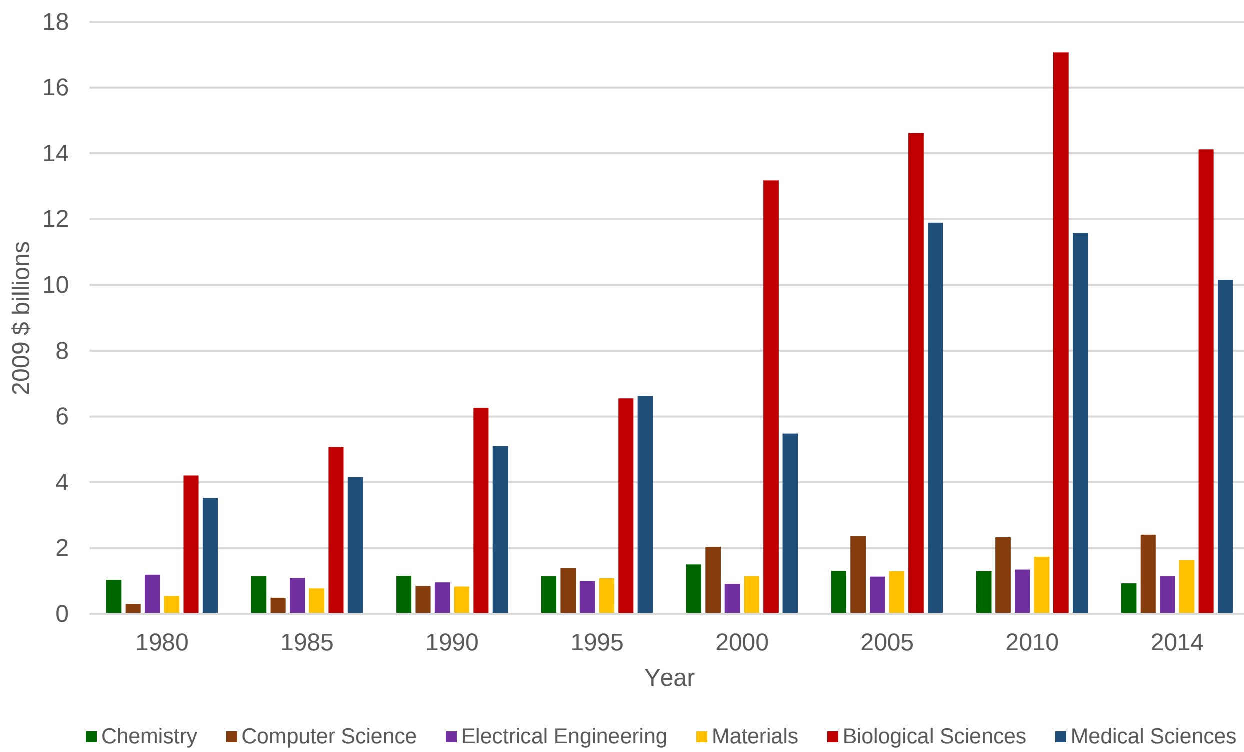

Figure 4: Federal Basic & Applied Research Obligations in Selected Sub-fields, FY 1980–FY 2014.

Trends in basic research support of these fields were similar (Figure 5).

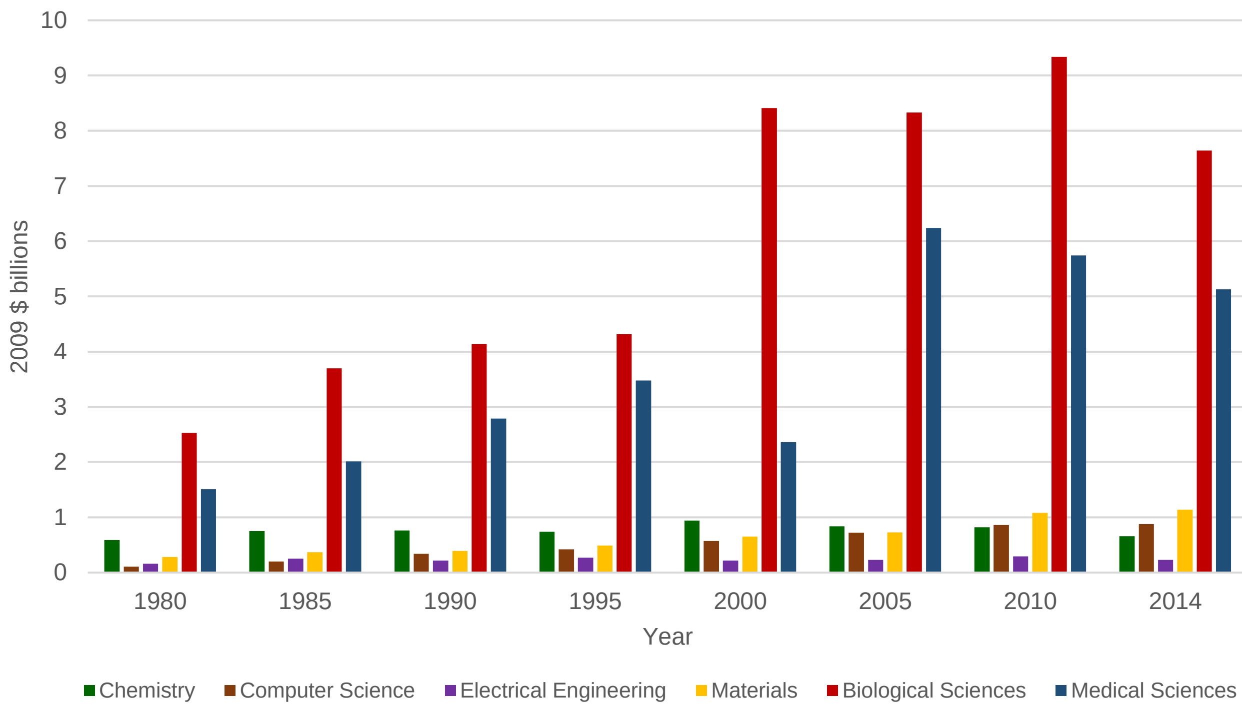

Figure 5: Federal Basic Research Obligations in Selected Sub-fields, FY 1980–FY 2014.

Sources of the Imbalance

The principal sources of the imbalance between support of the physical sciences and engineering on the one hand and the life sciences on the other hand are not obscure. By the late 1980s, many PS&E disciplines had become dependent on the Department of Defense. With the end of the cold war, defense R&D budgets were sharply reduced. Between FY 1993 and FY 1999 federal support of physics and chemical, electrical, and mechanical engineering declined by more than 20 percent in real terms. A fifth field—chemistry—suffered a smaller drop in funding (Merrill, 2001).

Meanwhile, a concerted political effort to boost federal funding for biomedical research, by doubling spending by the National Institutes of Health over five years, was stunningly successful, at least initially. NIH's regular appropriations increased from $13.6 billion in FY 1998 to $27.1 billion in FY 2003 in current dollars. NIH also benefited disproportionately from the two-year infusion of economic stimulus funding following the 2008 financial crisis. Three quarters of the nearly $12.7 billion in FY 2009 and FY 2010 American Recovery and Reinvestment Act (ARRA) funding allocated to research support went to NIH, compared to 10 percent to DOE, 13 percent to NSF, and 0.6 percent to DOD[5] (Merrill, 2013).

NIH budget growth was suspended in FY 2006 as a result of more stringent limits on domestic spending. By FY 2015, NIH research funding had fallen $5 billion in real terms from its FY 2004 peak, causing distress in a community of researchers enlarged by the previous infusion of regular and extraordinary funding. However, growth resumed in FY 2016 and FY 2017 when $2 billion were added each year to the NIH budget, and the final FY 2018 appropriation provides an additional $3 billion.

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[5] This was partly the result of political preferences for health research and partly based on agencies' comparative readiness to dispense the funds quickly to help turn the economy around.

Failed Attempts at a Course Correction for PS&E Research

The stagnation in PS&E support might have been reversed if efforts over the past decade to boost funding had been as successful as efforts to increase spending on research related to health. But after a promising start, they fizzled. In 2007, a congressionally requested National Academy of Sciences report, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future* (popularly known as *RAGS*) (National Academy of Sciences, 2007) called for a doubling Defense Department science and technology support on the premise that the military was still the principal funder of work in many PS&E fields critical to the nation's economic prosperity as well as national security. Introduction and passage of legislation—the America Creating Opportunities to Meaningfully Promote Excellence in Technology, Education, and Science (popularly known as America COMPETES Act) followed swiftly. It authorized a doubling of research funding over seven years through the National Science Foundation, National Institute of Standards and Technology (NIST), and the Department of Energy's (DOE's) Office of Science on the presumption that although these agencies supported work in the in the life sciences and other fields, much of any significant budget increase would flow to work in the physical sciences and engineering.[6]

The authorizers' ambitious spending targets carried little weight with congressional appropriators who were struggling to control spending, especially after the 2011 Budget Control Act imposed caps on discretionary spending enforced by sequestration rules. And despite the fact that both the Bush and Obama Administrations' budget requests called for increases (although more modest than the authorization levels) for NSF, NIST, and DOE, the appropriations repeatedly fell short of both the White House requests *and* the doubling target. The Congressional Research Service's tracking of authorizations, budget requests, and appropriations over the decade showed that the aspirational doubling did not occur in the first seven years of the first COMPETES legislation nor would it occur in the eleven years specified in the 2010 COMPETES Reauthorization but instead would take at least twenty years (Sargent, 2015). Finally, in December 2016, in a second bipartisan reauthorization of COMPETES Act programs,[7] the authorizers threw in the towel on reaching the doubling target by omitting <u>any</u> spending levels for NSF, NIST, and DOE's Office of Science.[8]

Other Sources of Research Support in Universities

Could it be that other sources of research support—businesses, philanthropies and other nonprofit institutions, and universities' own funds (derived from student tuition, gifts, investments, technology licensing, etc.)—have helped rebalance the nation's investments? For a partial answer we look first at

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[6] The requesters of the *RAGS* report and authors of the COMPETES Act—Senators Lamar Alexander (R-TN) and Jeff Bingaman (D-NM) and Congressmen Bart Gordon (D-TN) and Sherwood Boehlert (R-NY)—sat on the authorizing committees for the three agencies, not the Armed Services Committees nor the defense or any of the relevant appropriations subcommittees. It was natural that they would use legislation authorizing spending by the agencies in their committees' jurisdictions as a vehicle for implementing the report's recommendations. As a result, however, the role of DOD 6.1 and 6.2 research budgets in supporting the physical sciences and engineering was overlooked.

[7] Retitled the American Innovation and Competitiveness Act.

[8] There was an important exception to this pattern of generous authorizations and much more meager appropriations in the Department of Energy, but it did not benefit PS&E research. The *RAGS* report proposed and the COMPETES Act authorized the creation of a new agency in DOE, the Advanced Research Projects Agency-Energy (ARPA-E) modeled on the Defense Advanced Research Projects Agency (DARPA), with the mission of developing high-risk energy technologies not far enough advanced to attract private capital investment. By coincidence, the 2008 American Recovery and Reinvestment Act (ARRA), enacted in the wake of the financial crisis and ensuing recession, made short-term funds available for the Obama Administration to jump start ARPA-E. As the economic recovery progressed, astute managers of the agency were able to cultivate congressional support for sustained and even increased funding.

university portfolios which consist overwhelmingly (more than 90 percent) of basic and applied work. It turns out that the nonfederal sources have grown in importance of over time. Institutional funds are the fastest growing source and currently represent four times as much ($16.75 billion in 2015) as either corporate contributions ($4.0 billion) or foundation grants ($4.2 billion). NSF data, drawn from the universe of four-year institutions in the United States, indicate that all three of these sources of funds are more heavily focused on support of biomedical research than are the federal agencies collectively—55 to 66 percent compared to just below 50 percent (Figure 6). One recent informal survey (of 42 universities and 8 private research institutes) conducted for a consortium of private foundations engaged in supporting science found that 84 percent of private contributions to university research in 2016 went to the life sciences (Science Philanthropy Alliance, 2017).

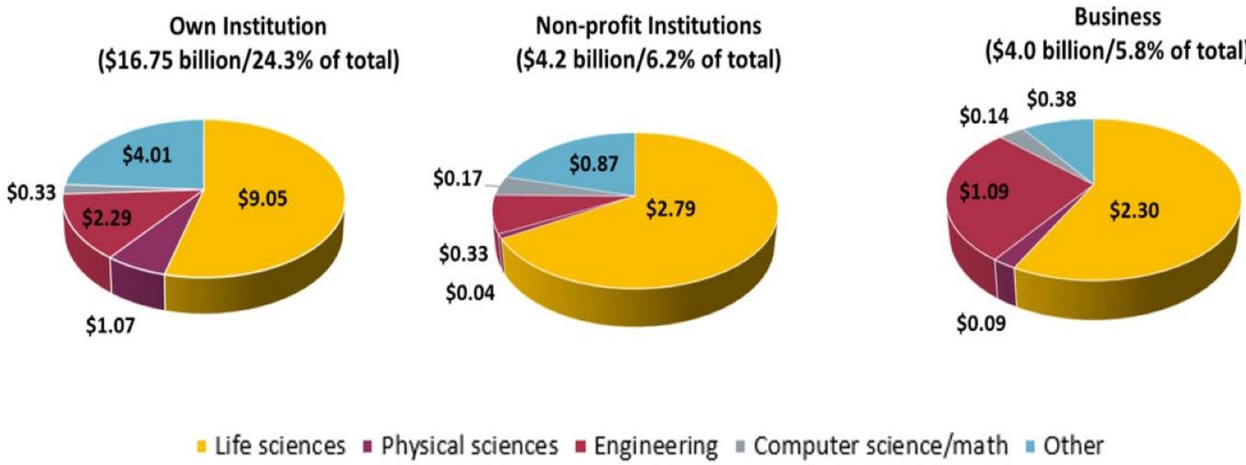

Figure 6: Non-Federal Funders of University R&D, FY 2015 (90% is basic and applied research).

Source: NSF Higher Education R&D Survey.

Business-funded Research

Business-funded and performed R&D has steadily increased over recent decades. It long ago surpassed the federal government's share and now represents 70 percent of the nation's total R&D effort. Does this mean we can be less concerned about the public sector's shift away from the physical sciences and engineering because the private sector is filling the gap? Recent work by Ashish Arora, Sharon Belenzon, and co-authors shed some light on this question and their evidence is not encouraging (Arora, Belenzon, Patacconi, and Sheer, 2017). First, companies' investments have moved away from research, basic and applied, and toward development. That has been a fairly steady trend since the early 1960s with the exception of brief upticks in the late 1980s and again in the late 1990s. In 2015 research represented only 20 percent of the business sector's R&D portfolio. As private firms' share of the nation's overall R&D effort was soaring, their share of the research effort was declining, from nearly 50 percent in the late 1990s to about 30 percent today (Figure 7).

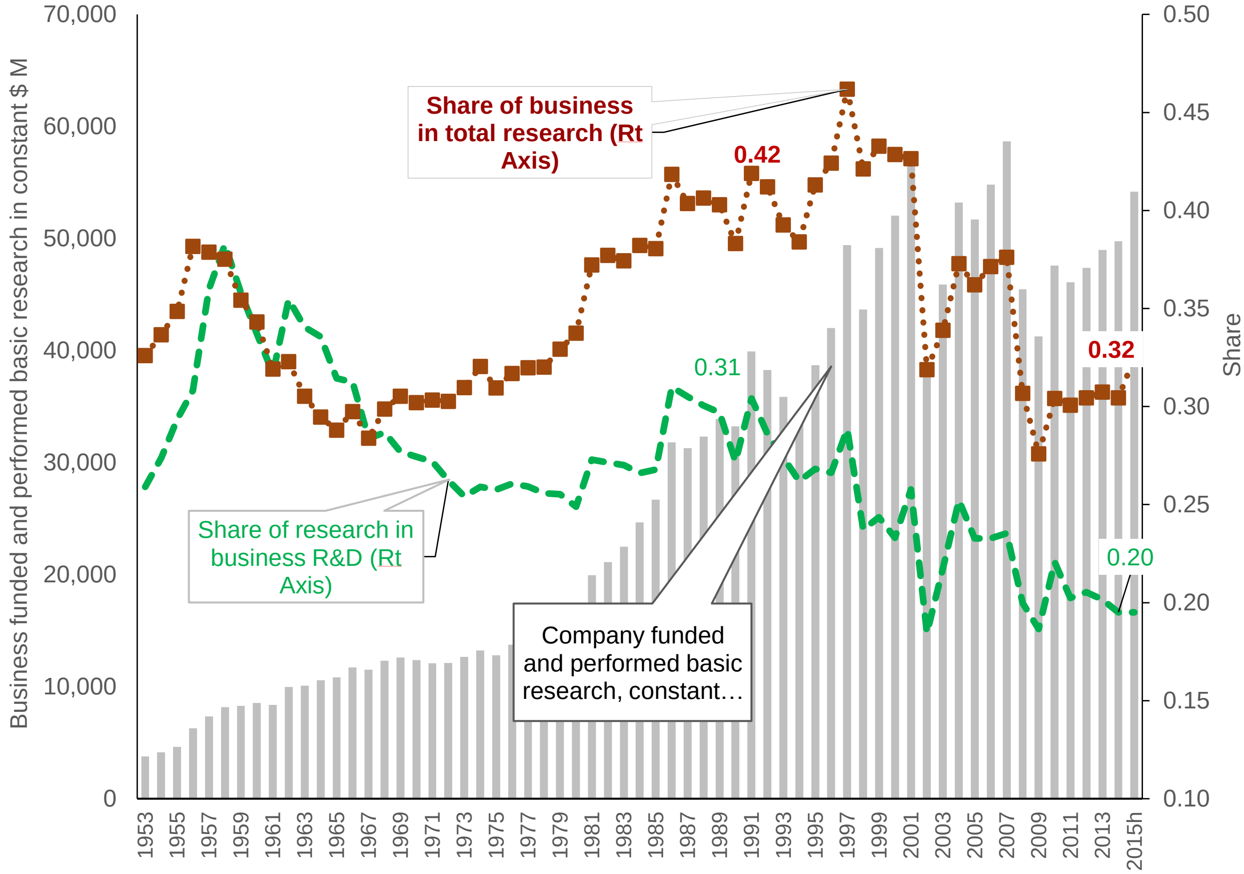

Figure 7: Business-Funded and Performed Research in the United States, 1953–2015.

Source: Arora, et al.

Second, this pattern is not the same for all industries. Chemicals and pharmaceuticals exhibit the slowest decline in research as a share of their R&D and in fact a modest increase in 2008 through 2011. The machinery and electrical/semiconductor sectors exhibit steeper declines in research. In fact, the latter's research as a share of its R&D dropped by one-half between 1996 and 2012. The number of electrical/semiconductor companies performing basic research as a share of all R&D performers in the industry also fell by one-half (Figure 8.1 and 8.2).

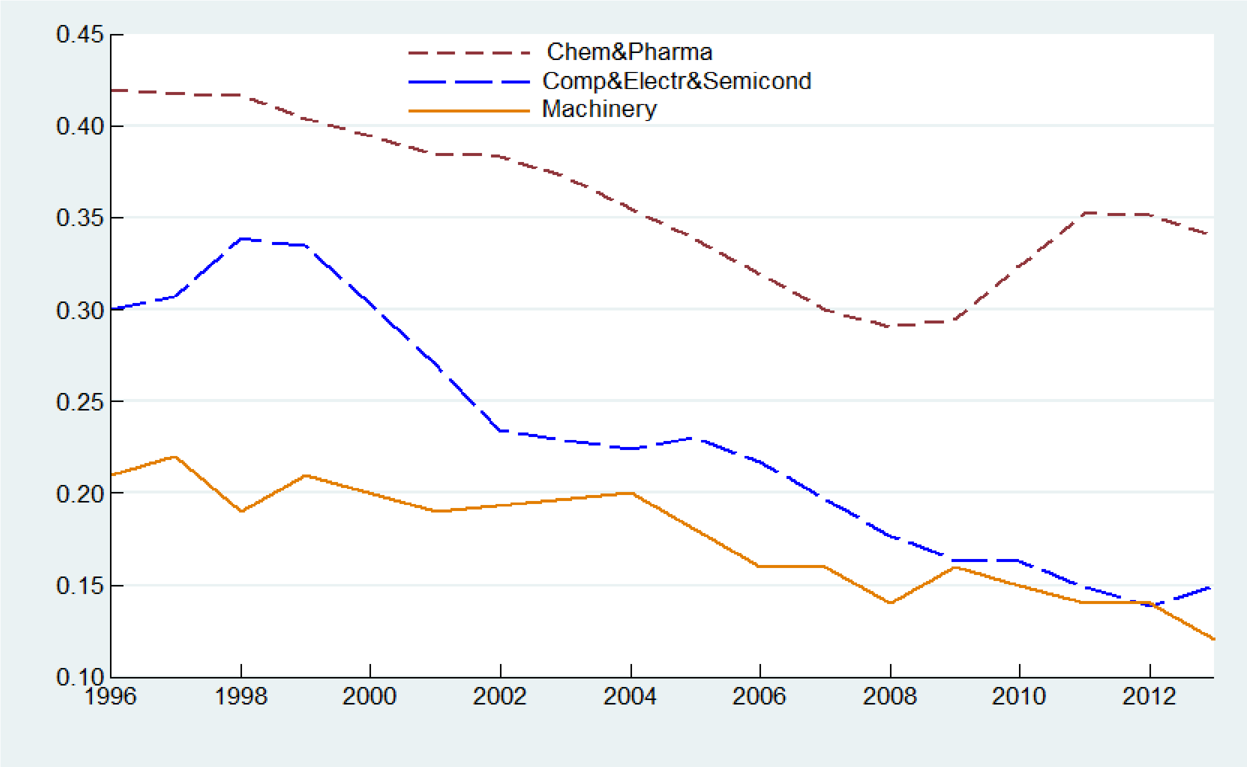

Figure 8.1: Share of basic and applied research in R&D by industry, 1996–2013.

Source: Arora, et al.

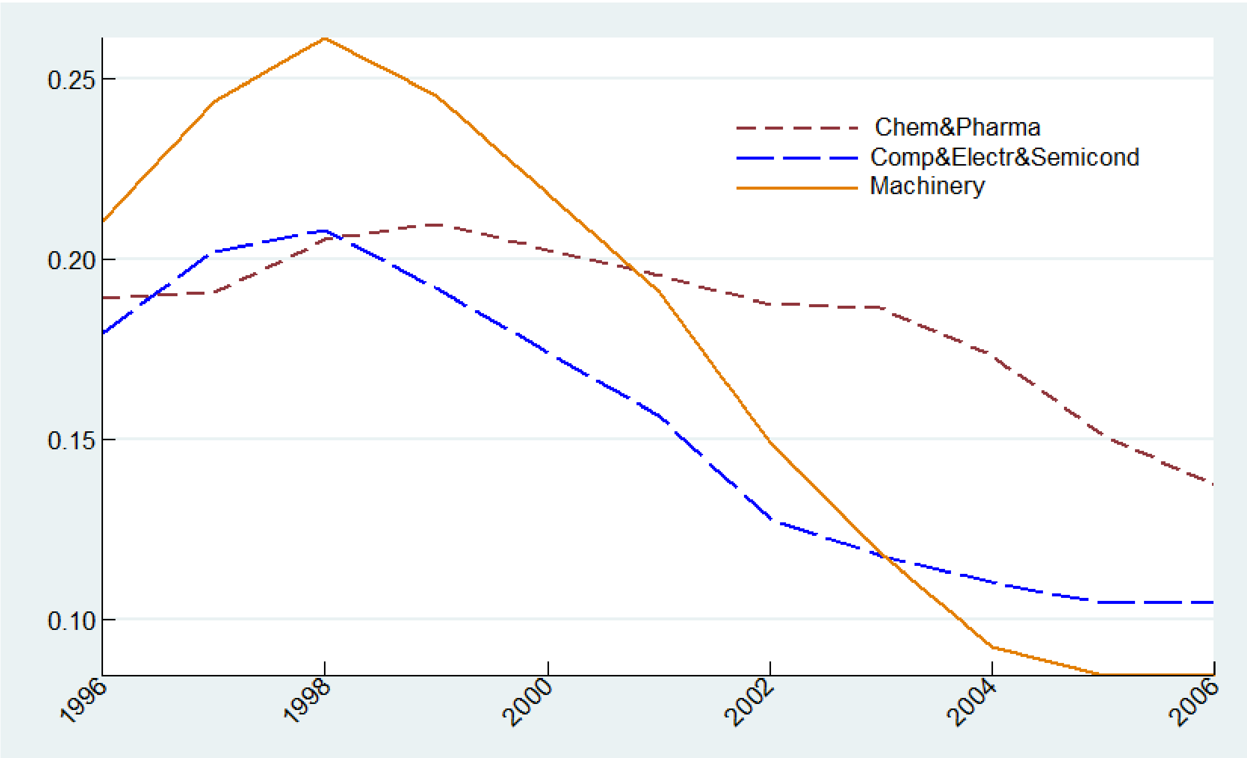

Figure 8.2: Share of companies performing basic research out of all R&D performers by industry, 1996–2006.

Source: Arora, et al.

Figures 8.1 and 8.2 industry classification is based on SIC codes (1996–1998) and NAICS codes (1999–2013): Chem&Pharma—SIC 28 and NAICS 325; Electr&Semicond—SIC 357 & 36 and NAICS 334; Machinery—SIC 351–56 & 358–59 and NAICS 333.

Third, there is evidence of declining spillovers from industry-sponsored research, more so in ICT-related fields than in biopharma. Research published in the open scientific and technical literature is available to all. It has higher spillover potential than research that remains proprietary. Results of research performed in universities are, of course, generally published. Industrial researchers have been important contributors to this literature, both independently and in collaboration with academics and scientists in other institutions. But that is changing. The frequency of industrial researchers' publishing has declined steeply across all sectors and especially in basic research journals relative to more applied journals. This suggests that the trend stems mainly from firms investing less in research rather than from a change in corporate policy regarding publishing or in industrial researchers' publishing practices Again, the decline in industrial publishing is greater in electronics/semiconductors, telecommunications, and software than in pharmaceuticals/biotechnology (Figure 9).

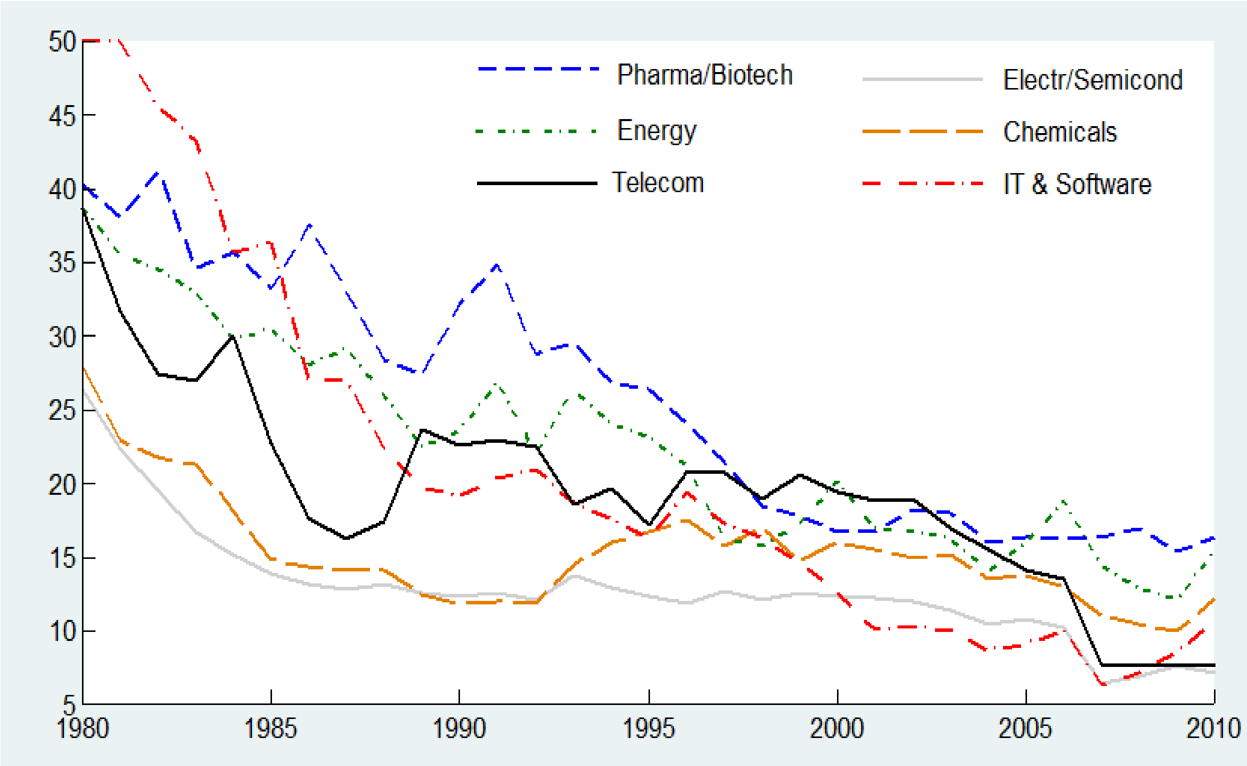

Figure 9: Trends in Publishing by Selected Industries, U.S. firms, 1980–2010.

Source: Arora, et al.

Figure 9 presents per firm per year publications over time by U.S. publicly traded firms in selected industries. Annual publication is conditional on at least one publication. Industry classification is based on SIC codes.

Alternative Policy Responses

The shift in the nation's research effort, away from physical sciences and engineering and toward the medical and other life sciences, seems to be pervasive. It is not limited to government-supported research but also extends to universities and industry. This is worrisome from the standpoint of productivity and economic growth. It may also be problematic from a national security perspective, but those implications are beyond the scope of this paper.[9] The needed transition in the energy and transportation sectors, from fossil to cleaner fuels, greater energy storage capacity, and autonomous vehicles, also depends mainly on technological advances derived from the physical sciences and engineering.

Because of its size, we may be tempted to focus on tweaking private rather than public investment in research. Two possible instruments are patent policy and tax policy. Unfortunately, neither is a promising tool to address the PS&E research deficit. Patent protection is particularly important in the biopharmaceutical and chemical industries where lead times are long, partly because of regulatory hurdles, and formulations once discovered are relatively easily copied. Patents are less important to innovation investments under most business models in software and computer hardware because of short product cycles and the need to combine multiple technologies. Historically, in any case, there is not a discernible relationship between changes in the strength of patent protection and investments in upstream research across diverse industries. Patent scope was extended and enforceability of patents was strengthened in the generation after 1980, coinciding with corporations' withdrawal from research in favor of focusing on technology development.

Likewise, tax policy is a blunt instrument for influencing the composition of corporate investment in research. By most accounts the business research and experimentation (R&E) tax credit, first instituted in 1981, has boosted overall corporate R&D spending although its effect has been muted by the fact that for decades the credit had to be renewed annually and was sometimes allowed to lapse. Its popularity finally led Congress in 2015 to make the credit permanent. Nevertheless, the credit, too, coincided with the decline in research spending by businesses and their shift to development.

Did patent system and tax policy changes actually encourage firms' withdrawal from research and focus on incremental development? We don't know, and there are other plausible explanations with some empirical support including the growing intensity of global, especially Chinese, competition and changes in financial markets putting a premium on quarterly stock performance. Although there is no consensus on the relative importance of these forces, it is unlikely that tax policy can mitigate their combined pressure to reduce costs and prioritize short-term investments with predictable payoffs (Rajgopal, 2017; Shu, 2017). Nor can tax policy affect the field composition of research activity without giving preference to some industries or even companies over others.

There is an exception to these generalizations, but its impact is limited. Credits for business contributions to university research may marginally influence the composition of corporate investment by favoring basic and applied research activities simply because that is the focus of university research activity. Such a provision was included in the R&E tax credit legislation and may have one factor in the semiconductor industry's formation the following year of the Semiconductor Research Corporation,

[9] Note, however, that the President's National Security Strategy of the United States, issued in December 2017, underscored the need to "prioritize emerging technologies critical to economic growth and security, such as data science, encryption, autonomous technologies, gene editing, new materials, nanotechnology, advanced computing technologies, and artificial intelligence. From self-driving cars to autonomous weapons, the field of artificial intelligence, in particular, is progressing rapidly." (National Security Strategy, 2017, 20).

providing grants to support electrical engineering research in selected universities. But Japanese competition was unquestionably the major driver of that initiative.

In short, there is no alternative to direct public funding to address the broad deficiency in federal support of the physical sciences and engineering. The answer is not to shift resources from the comparatively better funded life sciences to the physical sciences and engineering. Health, food, and related needs are no less compelling than economic and security needs. And it is obvious that as a result of the genetic revolution, biological science holds tremendous promise in addressing them. In any case, many authorities have argued that because of synergies across fields of research, often unanticipated, sustaining world-leading research in key fields and world class research in all major fields of science and technology should be a national priority.[10]

The FY 2018 Funding Breakthrough: A Positive Step, Not a Solution

Until this year, enacting incremental increases in funding across the several federal agencies supporting PS&E research faced high hurdles, principally the 2011 Budget Act caps on both domestic and defense discretionary spending. The first sign of a change was a temporary budget agreement in February that raised each of the caps more than 10 percent for the budget years 2018 and 2019. To the surprise of most observers, the final 2018 budget agreement enacted a month later took full advantage the greater flexibility, resulting in significant increases in research funding virtually across the board. The American Association for the Advancement of Science estimates that these actions have resulted in a boost of $7.77 billion for federally supported basic and applied research in 2018.

From a PS&E perspective, the increase is notable in several respects. First, the principal agencies supporting PS&E R&D all benefited from the largest budget increase year over year since the Recovery Act and the NIH doubling eras. The Energy Department's Office of Science received a 16 percent increase, the Department of Defense 6 percent, the National Science Foundation 4 percent, the National Institute of Standards and Technology 5 percent, and the National Aeronautics and Space Administration 8 percent.[11] Second, within DOE, the Science Office's advanced computing program received an astonishing 25 percent increase, rising from $647 million to $810 million. The energy sciences—fusion, nuclear, high energy, and basic—all received increases in excess of 10 percent. Third, inasmuch as DOD early stage (6.1–6.2 research) did not benefit from earlier increases and was ignored in the COMPETES legislation, its 6 percent boost is noteworthy even though the chief beneficiaries of raising the defense spending cap are the later-stage accounts for technology prototyping, testing, and evaluation.

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[10] A series of National Academies reports in the 1990s argued that comparative international performance should be the test of the health of research fields in the United States and the goal of public funding should be to maintain a clear U.S. lead in some major fields of research while ensuring that the U.S. researchers remain among the world leaders in all major fields. Lacking an agreed upon methodology for assessing comparative performance, the Academy went further in proposing a set of measures and applying them to selected fields on an experimental basis. However, no agency in the federal government took up the proposed methodology, refined it, and applied it more broadly. See National Academy of Sciences, National Academy of Engineering, and Institute of Medicine, *Science, Technology, and the Federal Government: National Goals for a New Era* (1993); Institute of Medicine, National Academy of Sciences, National Academy of Engineering, and National Resource Council, *Allocating Federal Funds for Science and Technology* (1995); and National Academy of Sciences, National Academy of Engineering, and Institute of Medicine, *Experiments in International Benchmarking of U.S. Research Fields* (2000).

[11] The National Institutes of Health were also major winners, receiving an increase of 8.3 percent, or $3 billion (approximately 40 percent of the total increase available for basic and applied research in all fields).

It is the case that since the end of the Cold War, the military's dominant supporting role in many PS&E research fields has declined. By 2015 DOD had a majority share of federal funding only in electrical engineering (66 percent of federal support). But in other key fields its role is far from negligible—one-third of computer science and mathematics funding, one-quarter of all engineering, and nearly one-fifth of metallurgy and materials support. Thus, it is also significant that the Trump Administration has taken a supportive stand on the role of the military in supporting so-called dual use research with potential civilian as well as defense applications. In their annual memorandum to heads of agencies with guidance for developing FY 2019 budget priorities, the director of the Office of Management and Budget and the Deputy Assistant to the President for science and technology advised that

> Historically, Federal R&D investments in military technology have led to the development of breakthrough technologies that have improved lives beyond the battlefield. While military R&D should serve the national defense first and foremost, the Administration recognizes the contributions of military R&D to the development of tremendously useful civil applications. Accordingly, we encourage programs with dual-use potential to be leveraged for Federal non-military advancements.[12]

Encouraging as these developments are, there are reasons to be concerned about the future. First, the budget caps are lifted only for FY 2018 and FY 2019; and the increase allowed for non-defense discretionary spending in FY 2019 is less than allowed in FY 2018. Without further congressional action the previous spending limits will be reinstated for FY 2020, conceivably forcing deep cutbacks in existing programs.

Second, because the budget agreement was concluded almost half-way through FY 2018, agencies have a very short time, 6 months, to spend a great deal of unanticipated, unplanned for money. Recall that agency administrators had developed plans for the President's FY 2018 budget submission on the basis of research spending *reductions* of 13 to 16 percent overall. It will take them some time and considerable effort to revise assumptions, decide how to spend the unanticipated windfall wisely, and execute on those plans.

In these circumstances—the sudden windfall and the prospect of a spending cliff to follow—the NIH doubling experience is instructive, showing that large infusions of research funding over a short period of time are not a good approach when not sustained. The NIH budget doubling led to a rapid expansion of capacity—laboratory infrastructure and biomedical research personnel—that was under-utilized when the doubling goal was achieved and budget growth ceased. As a consequence, it became harder for researchers, especially younger researchers, to compete successfully for grants. For graduates completing their training in many fields of human biology, the prospect of tenured employment receded or evaporated and post-doctoral fellowship status lengthened (Freeman and Van Reenen, 2008). This had two adverse consequences for biomedical research human capital. It discouraged talented students from entering the field or encouraged them to leave it and it delayed acquisition of experience in independent research by those who remained.

Finally, although we are poised to begin to redress the PS&E research deficit, there are class 4 rapids and perhaps waterfalls that should not be left for the multiplicity of agency administrators responsible for diverse modes of research support—competitive grants, in-house laboratories, and external contracts and cooperative agreements—to navigate independently. The circumstances created by the FY 2018 appropriations call for coordination and foresight across civilian and military programs—a function of some combination of the Office of Science and Technology Policy (OSTP), the National Science and

[12] Memorandum from Mick Mulvaney, Director, Office of Management and Budget, and Michael Kratsios, Deputy Assistant to the President, Office of Science and Technology Policy, for the Heads of Executive Departments and Agencies. The subsequent National Security review sounded a similar theme.

Technology Council (NSTC), and the National Economic Council (NEC). Unfortunately, the Trump Administration has yet to take any initiative in creating in the White House and Executive branch councils the capacity to look across funders and disciplines for gaps in support, opportunities for collaboration, and risks of creating excess capacity, but that is the next important step in making the best of the opportunity Congress has provided and sustaining that progress.

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In "Righting the Research Imbalance" Merrill makes a strong case that, since 1980, the U.S. has failed to adequately support an essential building block of an innovative 21st century economy – government-funded basic and applied research. As his research shows, the problem is most acute in the physical sciences.

While the recently passed 2018 Appropriations Act contains a much needed increase in funding, it should not obscure our failure to prioritize funding in the physical sciences over the long term.

The problems addressed in this paper must be dealt with if the U.S. is to retain its position as the world leader in science and technological innovation.

Jeff Bingaman, former U.S. Senator (D-NM)

Merrill provides substantial data to support the concerns of many in the physical sciences that critical, enabling research is being under-funded relative to the nation's economic and security interests… The reality of today's business and investment environment demands that the federal government recognize the importance of the physical sciences in meeting some of our greatest challenges and develop sustainable funding of this critical intellectual infrastructure.

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