POLICY FORUM

RESEARCH FUNDING

Government-funded research increasingly fuels innovation

Nearly a third of U.S. patents rely directly on federal research

By **L. Fleming[1], H. Greene[2], G. Li[1], M. Marx[3], D. Yao[4]**

Innovation increasingly relies on scientific knowledge (*1, 2*). Research to generate that knowledge has historically been funded by both industry and government. Although industry and government research spending was relatively equal in 1980 in the United States, by 2010 their shares had shifted to 60% and 30%, respectively (*3*). Yet, despite this increase in industrial spending, firms appear to be pursuing—or at least publishing—less basic science (*4*). If corporations are doing less basic research, then where do they find the ideas to fuel their innovation? Here, we detail individual bibliometric linkages across tens of millions of documents and quantify the broad sweep and impact of U.S. federally supported research on patented innovation over most of the past century. We illustrate how patentees, both U.S. and non-U.S., and corporations in particular, increasingly depend upon federally supported research as a source of scientific knowledge. Although multiple mechanisms interact and contribute to the trend, federal research increasingly appears to fuel the innovation that ultimately leads to jobs, industrial competitiveness, and entrepreneurial success.

Though research has established the rise of "open innovation" communities, research consortia, and markets for ideas as sources of innovative ideas (*5*), the role of government funding for research has not been ignored. Recent research—at the micro level of individual science papers and patents—has quantified how 10% of grants awarded by the U.S. National Institutes of Health (NIH) generate patents (*2*). Macro-level and nonquantitative histories have also described the broad sweep of government impact (*6*). Here, we consider every U.S. patent assigned to U.S. inventors since 1926, and show that the proportion of patents relying on federally funded science has outstripped the overall increase in patenting, plateauing since a high of 30.0% in 2011 (see the first figure). Despite this plateau, the absolute number of patents that rely on federally supported research has almost doubled recently, from 22,647 in 2008 to 45,220 in 2017. We count reliance when a patent is owned by the government, acknowledges government support, or directly cites a patent or science paper that acknowledges support.

Corporations, identified as the owner of a patent from its "assignee" field, account for most of the increased reliance on government-supported research since the 1970s (see the second figure). Corporations have increased their own acknowledgment of support and their citation of government-supported science papers and patents [although alternatives cannot be entirely ruled out, see supplementary materials (SM) for evidence that the trends are robust to more versus less stringent definitions of reliance and also do not result from a change in reporting requirements or in response to requirements, an increase in the citable stock of federal research, or a mechanical process due to an increase in the number of citations per patent].

The sharp increase following World War II (WWII) illustrates the invention behind the vision articulated by Vannevar Bush in 1945, of how federal investment in science research could train the technical workforce and support innovation, resulting in "…new products, new industries, and more jobs…new and improved weapons" (*7*). The almost monotonic increase in reliance has been partially enabled by the steady though slower rise in inflation-adjusted federal research dollars over the time period, even as federal science investment as a percentage of gross domestic product has decreased (*8*).

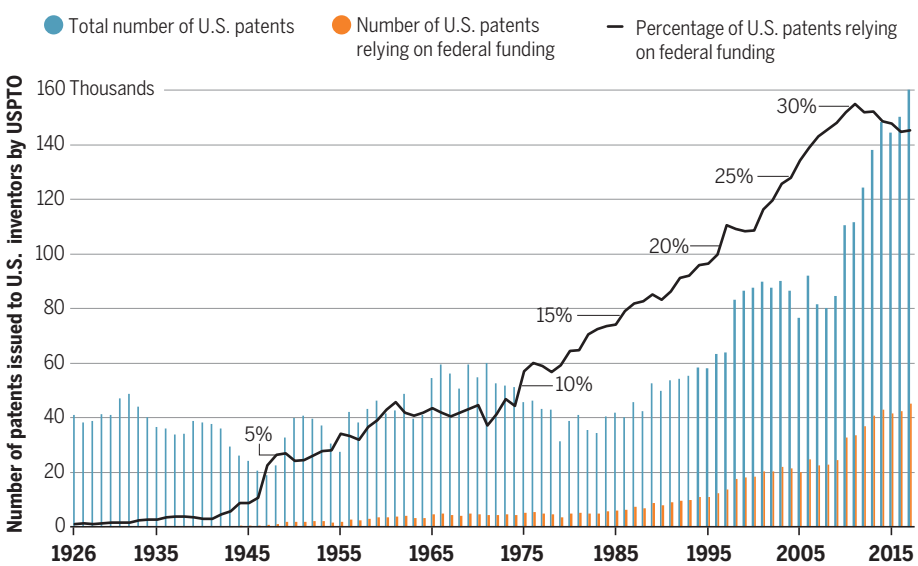
Prior to the 1970s, much of the government-supported patenting in the United States occurred inside the government. Universities, often supported by government research grants, began patenting more in the 1980s, motivated in part by the Bayh-Dole Act, which sought to spur commercialization through assignment of property rights to universities. Lone inventors constituted a large proportion of reliance upon government research in the early part of the last century, and their reliance has remained steady.

Although some portion of the overall increase shown in the first figure results from a change in the composition of patented technologies, growing investment in

[1]College of Engineering, University of California, Berkeley, CA, USA. [2]School of Law, University of Connecticut, Hartford, CT, USA. [3]Questrom School of Business, Boston University, Boston, MA, USA. [4]Harvard Business School, Harvard University, Cambridge, MA, USA. Email: lfleming@berkeley.edu

Patentees increasingly depend upon federally supported research

Total granted U.S. patents by U.S. inventors (blue bars), and subtotal that rely on federal research (orange bars), and proportion of patents (black line = orange bars/blue bars) that rely on federally supported research.



GRAPHIC: N. CARY/SCIENCE

health research, and an accompanying rise in patents supported by the Department of Health and Human Services (HHS) (which includes the NIH), all technologies have relied increasingly upon government support, albeit to varying degrees. Federal support for U.S. invention gets routed through a variety of agencies. In 2017, for example, the Department of Defense (including the armed services) supported 6.2% of the total of U.S. inventions, HHS 5.4%, Department of Energy 3.9%, National Science Foundation 2.9%, NASA 1.0%, and Department of Agriculture 0.50% (others 5.5% and unspecified 2.5%; see SM for illustrations of R&D investment and patenting by agency and by technology class).

Large, small, and micro firms all draw upon government research, as observed in patent-renewal data. Startups also depend heavily on government research, as 34.6% of the 121,765 patents assigned to venture-backed companies from 1976 to 2016 cited federally supported research; by comparison, for all corporate patents during the same time period, only 21.7% rely on federally supported research. The higher reliance of startups on government-supported research may be explained by resource constraints, which inhibit internal R&D expenditure in young ventures and encourage identification and external licensing of promising technologies. It also illustrates the intended consequence of the Bayh-Dole Act and an important path of commercialization for federal science and technology research.

Foreign inventors' reliance on federal research in their U.S. patenting has steadily increased since WWII (see the third figure), though the proportion of total foreign patenting in the U.S. system that relies on federal research still lags behind that of U.S. inventors (in 2017, 28.2% of U.S. patents by U.S. inventors, and 12.4% of the U.S. patents by foreign inventors, relied on federally supported research). China has recently begun to rely more heavily on U.S. federal research; however, its reliance is still small relative to most (in order of reliance in 2017): Japan, Germany, Korea, England, France, China, Taiwan, and India. The greatest recent increase has come from the category of "other" nations, perhaps reflecting easier access via the web and other electronic libraries to the patent and scientific literature.

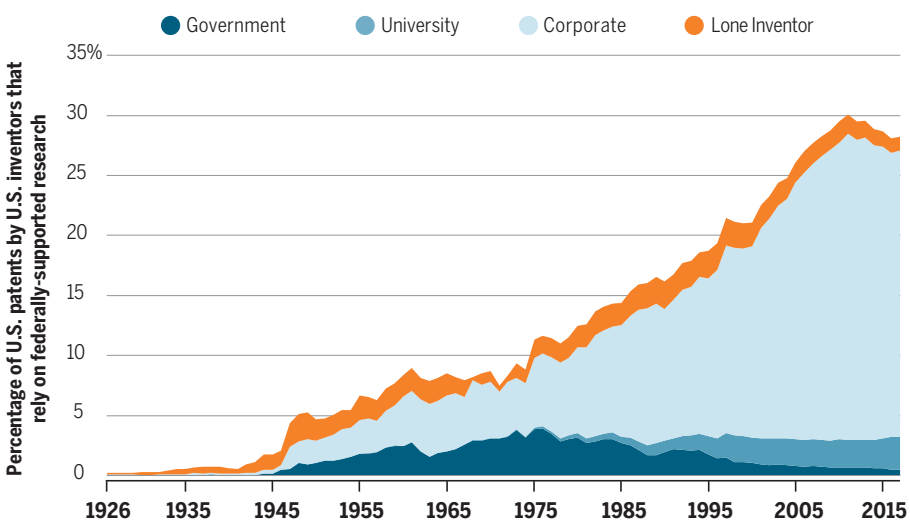
Many factors make it more difficult for foreign inventors to gain access to U.S. science—including language differences, the cost of international travel, fewer social ties between scientists and engineers, problems of security clearances and access to sensitive technologies, and surely less mobility from (U.S.) university positions into private firms in foreign countries. Moreover, countries vary in their degree of local specialization and may find U.S. research less helpful, if working in areas not supported by U.S. research. Although other nations' inventors have increased their reliance on federal research, the rate of increase appears less than that of U.S. inventors, even as the world's scientific and technical knowledge has become digitized and thus more easily searched and used.

Corporate patents that rely on federal research are consistently more important than those that do not, as measured by the number of prior art citations from subsequent patents (such citations establish the departure point of a new patent). Comparing population averages for all U.S. corporate patents granted in 2010, patents that rely on federal research receive 6.33 citations on average in the 5 years following the grant versus 4.42 for those that do not. Additional panels in 2000, 1990, and 1980 show similar but not always significant effects, possibly because of thinner data or changes in corporate patenting strategy (see SM). These population averages aggregate a great variety of different technologies, industry-specific patenting strategies, and number of inventors on the patent, however, which motivates a comparison of similar types of patents. Matching and pairing corporate patents that cite federally supported patents to similar corporate patents that did not (see SM), the former receive on average 3.39 more citations in the 5 years after issuance. The citation increase arises from both the firm's subsequent patents (1.53 additional self-citations on average) and citations in other firms' patents as well (1.86 additional citations from other organizations on average), indicating that both the inventing firm and its competitors find these technological trajectories more fertile.

The same pattern holds for corporate patents that cite federally supported science publications relative to those that cite science publications that are not government supported, with a matched and paired mean difference of 3.57 citations, and a mean difference in self- and nonself-citations of 1.17 and 2.41, respectively. Prior research has estimated that an additional citation is associated with an increase in the value of the patent of up to 3% (*9*).

Reliance upon federal support has been dominated by corporations

Stacked area chart of percentage of total U.S. patents by U.S. inventors that are owned by government or rely on federally supported research papers or patents, by type of patent owner.



Citation increases also benefit the larger economy as citations that occur from outside the inventing firm can be interpreted as knowledge spillovers and positive externalities from the inventing firm to the larger economy (*10*).

Consistent with the citation measure and again comparing matched patents, patents that rely on federal research are slightly more likely (<2%) to pay renewal fees (required payments that keep the patent in force) after 4 years. They are also more likely, on average, to introduce words that are new to the patent corpus, indicating foundational patents with greater novelty (*11*).

Although the bulk of reliance historically can be traced through citation of prior patent art, U.S. inventors have recently shifted their citation patterns to favor more im-

GRAPHIC: N. CARY/*SCIENCE*

mediate citation of government-supported science papers. The average percentage of prior art citations within each patent that are supported by federal research fell from a high of 15.8% in 2003 to 9.9% in 2017. By contrast, citation of scientific papers that are supported by federal research reached a historical high of 10.7% in 2017, up from 6.9% in 2004 (see SM).

If federal science research is so important to corporations, why don't they undertake all (or at least more of) their research internally? Putting aside the question of the optimal rate and types of corporate taxation, why should the government subsidize private firms through federally funded and managed research investment? Much research has argued and demonstrated that corporations probably underinvest in research (*12*), owing to uncertainty and the difficulty of commercializing research by the firm doing the research (as opposed to that firm's competitors). Furthermore, from a societal viewpoint, the discoveries from research are best distributed widely throughout an economy, rather than being kept in a single firm, thus reducing duplicative efforts. Research aimed at fundamental understanding thus constitutes a public good, typically precedes commercialization, and can be applied by many corporations, across many industries, for many years following publication. Although these results might be interpreted as evidence of short-sighted lack of research investment on the part of corporations, they can also be interpreted as evidence of the effectiveness of public investment in science and technology research in spurring innovation.

Our bibliometrics enable explicit linkage of government support and output but remain vulnerable to many limitations in methodology, interpretation, and causal attribution. Patents are only one—and an admittedly imperfect—measure of innovation, particularly prior to the availability of comprehensive data in the mid-1970s. Moreover, the use of patents varies across industries and over time (though the matched analysis above controls for technology, number of inventors, and time). Our focus does not extend, for example, to innovations protected as trade secrets or through copyright. Other factors that complicate causal interpretation include the concurrent (though slower) rise in federal spending on science over the period, changes in compliance requirements (*13*), changes in corporate patenting and citation strategies, and improvements in database and search technology that enabled increasingly accurate acknowledgment of government support (see SM for discussion).

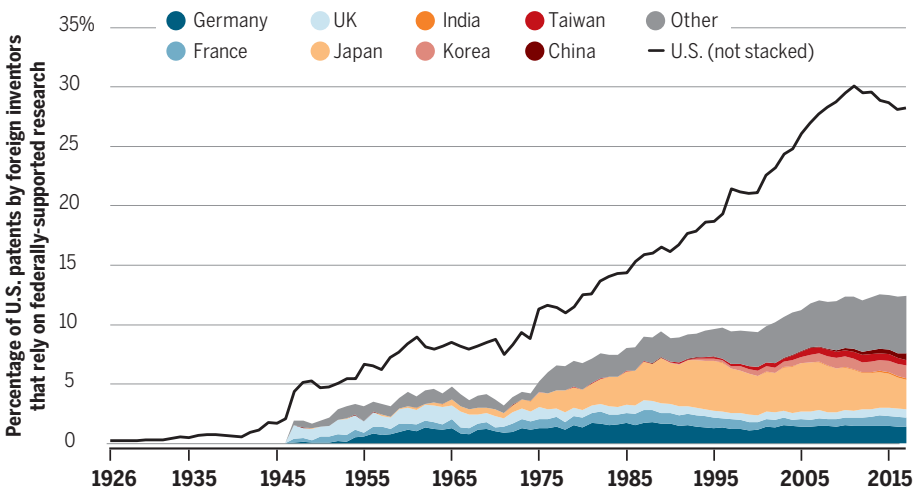
Furthermore, this study does not compare observed output to the counterfactual: patenting and publishing that would have (not) occurred in the absence of federally supported research. Hence, one cannot estimate the extent to which federal support of R&D has crowded out private investment, though there is increasing evidence that thoughtful applications of such support can encourage additional and complementary private investment (*2*).

These issues notwithstanding, these data provide a quantitative estimate of the changing impact of federal research on U.S. patenting. They show that almost one-third of U.S. invention—and the more important part as measured by future citations, renewals, and novelty—relies on federal research investment. Our measures conservatively use only direct linkages, ignoring dubious or missing acknowledgments of support as well as knowledge flow from second- and later-generation citations. These analyses also ignore the nonpecuniary (and possibly more substantial) benefits such as better weapons, improved health and medical practices, technical workforce training, directly and indirectly supported jobs, and entrepreneurial ideas that spark startups (Google's Page Rank patent acknowledges government support, for example).

If the sponsoring nation's firms can more effectively take advantage of that nation's research—as appears to be the case to date in the United States—then firms can exploit a fundamental competitive advantage in international competition. Federal research increases the likelihood that new industries will locate in that country and provide jobs and productivity spillovers to older industries. Policy-makers should consider these newly observable benefits of federal research when they formulate tax policy and science research budgets.

Foreign reliance on federal research has steadily increased

Proportion of U.S. patents by non-U.S. inventors that rely on federally supported research, stacked by country (for comparison, the black line above is not stacked, and illustrates the proportion of U.S. patents by U.S. inventors that rely on federally-supported research, from the first and second figures).



GRAPHIC: N. CARY/*SCIENCE*

REFERENCES AND NOTES

1. M. Ahmadpoor, B. F. Jones, *Science* **357**, 583 (2017).
2. D. Li, P. Azoulay, B. N. Sampat, *Science* **356**, 78 (2017).
3. National Science Board, Science & Engineering Indicators 2018: Figure 4-4, "U.S. Total R&D Expenditures, by Source of Funds: 1953-2015"; https://nsf.gov/statistics/2018/nsb20181/report.
4. A. Arora, S. Belenzon, A. Patacconi, *Nat. Index* 6 (2017).
5. E. von Hippel, *Democratizing Innovation* (MIT Press, 2005).
6. M. Mazzucato, *The Entrepreneurial State* (Perseus Books, 2013).
7. V. Bush, *Science: The Endless Frontier* (U.S. Government Printing Office, Washington, D.C., 1945).
8. https://www.aaas.org/programs/r-d-budget-and-policy/historical-trends-federal-rd.
9. B. Hall *et al.*, *Rand J. Econ.* **36**, 16 (2005).
10. A. B. Jaffe *et al.*, *Q. J. Econ.* **108**, 577 (1993).
11. B. Balsmeier *et al.*, *J. Econ. Manage. Strategy* **27**, 535 (2018).
12. K. Arrow, *Rev. Econ. Stud.* **29**, 155 (1962).
13. A. K. Rai, B. N. Sampat, *Nat. Biotechnol.* **30**, 953 (2012).
14. E. Garfield, *J. Pat. Off. Soc.* **39**, 583 (1957).
15. L. Fleming *et al.*, Replication Data for: Government-funded research increasingly fuels innovation. Harvard Dataverse, V4 (2019); https://doi.org/10.7910/DVN/DKESRC.

ACKNOWLEDGMENTS

The authors acknowledge support from NSF 1536022, the Coleman Fung Institute for Engineering Leadership, the University of Connecticut School of Law, and the Harvard Business School. We thank M. Ewens for sharing data and B. Balsmeier and D. Gross for helpful comments. All opinions and errors remain with the authors. The authors declare no competing interests. Data and code are posted on Harvard Dataverse (*15*).

SUPPLEMENTARY MATERIALS

science.sciencemag.org/content/364/6446/1139/suppl/DC1

10.1126/science.aaw2373

Government-funded research increasingly fuels innovation

L. Fleming, H. Greene, G. Li, M. Marx and D. Yao

Science **364** (6446), 1139-1141.
DOI: 10.1126/science.aaw2373