FULL REPORT

MIT Science Policy Review

Federal R&D funding: the bedrock of national innovation

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Edited by Jack Reid and Anthony Tabet

HIGHLIGHTS

- Federal research and development (R&D) funding has significantly declined as a share of GDP for several decades.
- We argue that federal R&D funding is the bedrock of national innovation and plays an irreplaceable role in steering scientific progress towards the betterment of society.
- We propose tailored communication efforts to galvanize long-term public support for federal investment in R&D.

The U.S. government's financial commitment to scientific research has significantly declined in the past few decades. Recent research has also revealed a lack of public awareness of the importance of federal research and development (R&D) funding; only one in four Americans believe that the government's role in science is indispensable. In this paper, we argue that federal funding provides the bedrock for the U.S.'s innovation infrastructure while guiding the national research agenda to benefit society. We first examine which projects the federal government chooses to fund, concluding that federally-funded R&D focuses heavily on use-inspired basic research and supporting work which is in line with the missions of federal agencies, missions that prioritize societal needs. Next, we examine how federal science funding uniquely addresses market failures of private sector R&D while catalyzing innovation more broadly. We close by proposing specific tailored communication strategies to galvanize public excitement about science, thereby mustering sustained public support for federal R&D funding.

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The authors declare no conflict of interest.

Introduction

> We choose to go to the moon. We choose to go to the moon in this decade, not because [it is] easy, but because [it is] hard, because that goal will serve to organize and measure the best of our energies and skills, because that challenge is one that we are willing to accept, one we are unwilling to postpone, and one which we intend to win.
>
> *President John F. Kennedy, 1962*

When President John F. Kennedy proclaimed these now-famous words at Rice University in Houston, Texas, in 1962, the United States was lagging behind in the Space Race [1]—the Soviet Union was first to launch a satellite into orbit and first to launch a human into space. However, unfazed in the face of adversity and the seemingly impossible, the United States doubled down on its commitment to this massive and heroic endeavor, mobilizing the nation's top talent and succeeding in sending a human to the moon for the first time in human history by 1969, a mere seven years after Kennedy's speech.

The Space Race, in a sense, marked the pinnacle of a golden age in American science and technology, from the technological superiority that helped the Allies win World War II to the advent of computing and the Internet that revolutionized the entire world, and in 2020, the footprint of American science pervades every corner of the globe. This golden age brought the U.S. not only unparalleled prestige but also incredible prosperity.

America's prosperity and success have been underwritten in no small part by its technological leadership [2]. And as America loses ground in the global race in technological innovation, this position, along with the prosperity and security America has enjoyed, are at stake [3, 4]. In an increasingly competitive global environment, federal support of scientific research—research that pays dividends decades into the future—is all-the-more fundamental to the U.S.'s current and future economic success [5].

American progress in an array of key research areas—e.g. photonics, robotics, artificial intelligence, nanotechnology—areas that would generate the yet-unimagined technologies and industries of the future decades from now, threatens to lag behind that of other countries [5]. Put another way, compared to other countries, we are not investing enough in our own country's future, threatening economic prosperity and job creation decades down the line. The federal government's failure to aggressively invest in scientific research is already exacting a cost: research projects in universities across the country are being shut down because of funding cuts [6]. The ramifications of these present cuts will be felt for decades to come [3].

This paper diagnoses the current problem with insufficient federal research funding and lays out the unique role of the federal government in the national scientific research enterprise. In particular, we first highlight the importance of federal funding in facilitating innovation and then outline the reasons for and results of insufficient federal research funding. The federal government sets national priorities for scientific and technological progress, addresses market failures concerning high-risk, public-good research endeavors, and "crowds in" human and capital resources to R&D, both public and private, creating a virtuous, self-reinforcing cycle of greater investment in research and innovation. We conclude that U.S. federal R&D expenditures should be greatly expanded in order to sustain the economic prosperity and social well-being of America and its people. Furthermore, we recognize the necessity of galvanizing political will through policy advocacy and public engagement to safeguard future support for federal R&D.

The Faltering of Federal Research Funding

After World War II, the federal government began prioritizing funding for R&D, propelling the United States into a position of global leadership in innovation and technology [7]. In current dollars, federal R&D funding grew from $2.8 billion in 1953 to $127.2 billion in 2018. However, over the last decade, federal support for R&D has been relatively flat, and from 2011-2014, funding actually fell for three consecutive years [7] (Fig. 1a). The past few years have seen a bolstering of bipartisan support for the federal research budget [8] (Fig. 1a), but this recent trend cannot be taken for granted. Under the presidential budget request for FY2021, federal research funding would be cut by 9% overall [9]. Additionally, in recent years, trends in R&D funding have been largely driven by overall trends in discretionary funding, which compared to mandatory, or entitlement spending, has represented a dwindling share of the federal budget [8]. Appropriators will face tough choices in the next two fiscal years, in the face of limited room for increased spending under the discretionary spending caps. This pressure will undoubtedly be exacerbated by the ongoing global economic recession caused by COVID-19 [9, 10].

One important metric for assessing a country's investment in R&D and innovative capacity is "R&D intensity," or the percentage of R&D expenditures as a share of gross domestic product (GDP) [8]. In the United States, federal R&D intensity has had an overall downward trend since the Space Race of the 1950s and 60s [11], declining from a high of 1.86% in 1986 to 0.62% in 2017 (Fig. 1b). By this less optimistic measure, the U.S. government has actually greatly deprioritized the importance it places on research innovation in recent decades.

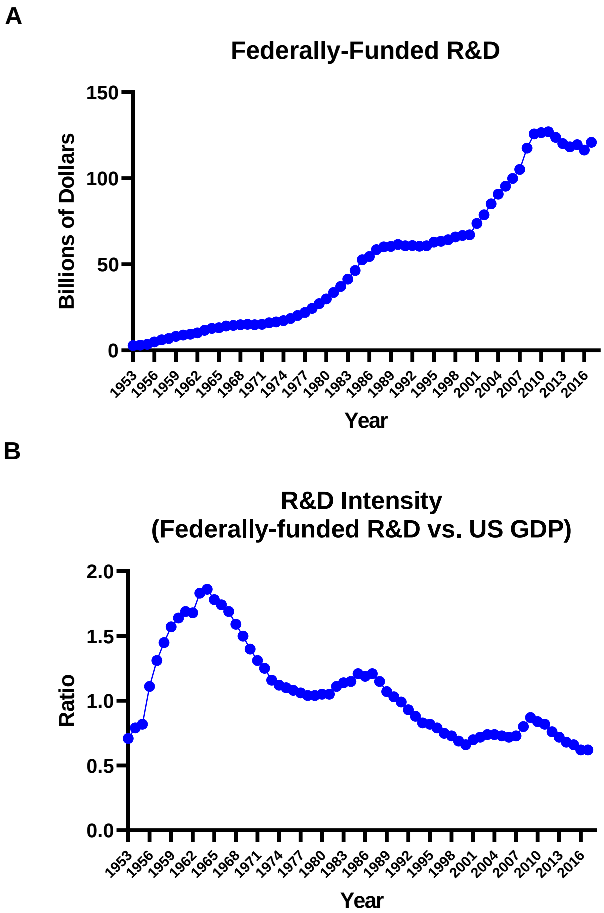

Figure 1: Trends in federally-funded research and development (R&D) funding over time. (A) Total amount of federal R&D funding in billions of dollars. (B) R&D intensity, given as the percentage of federal R&D expenditures as share of total gross domestic product (GDP). All amounts are in current U.S. dollars. Source: National Science Board, National Science Foundation, 2020, Research and Development: U.S. Trends and International Comparisons, Science and Engineering Indicators 2020, NSB-2020-3, Alexandria, VA. Available at https://ncses.nsf.gov/pubs/nsb20203/.

One frequently discussed repercussion of the recent stagnation of federal R&D funding is that America's position as the world's uncontested technology and innovation powerhouse has been steadily slipping. The most recent NSF Science and Engineering Indicators report showed that as of 2017, the United States still leads the world in total R&D spending (both public and private expenditures) [12]. However, the U.S.'s share of global R&D has declined from 69% during the post-WWII period to 37% in 2000 to 27.7% in 2017 [7, 13]. Globally, comparing the growth rate of total R&D expenditure from 2000-2017, the U.S. lags behind several other countries, including China, South Korea, India, and Germany [12]. The potential technological, economic, and national security implications of the loss of U.S. dominance in research and innovation has been extensively reviewed elsewhere [4, 14].

Another impact of recent trends in R&D funding is a dramatic shift in who is sponsoring research. While federal R&D has seen a period of recent stagnation, this has been offset by rapid increase in R&D by the private sector. Before the 1980s, the federal government funded the majority of R&D, whereas since the 1980s, private funding has dominated. As of 2017, around 70% of R&D expenditures were funded by businesses [8, 11] (Fig. 2). The ramifications of this trend are not immediately obvious; indeed, in a recent public opinion survey of adults in the United States, only one in four people believes that the federal government's role in science is essential [15], indicating a belief that the private sector could replace the function of the federal government in R&D. However, in this paper, we contend that the federal government is uniquely situated to undertake cutting-edge scientific initiatives, and to guide the research agenda to address societal needs that the private sector would otherwise ignore. We also discuss how the federal government "crowds-in" funding from other sources, and invests in infrastructure and human resources upon which the rest of the scientific enterprise relies.

Critical Roles of the Federal Government

The federal government is critical to both the progress of national R&D and tying this progress to societal needs. In this section, we introduce the taxonomy of R&D categories and discuss each of the roles of the federal government in detail. Specifically, the federal government funds research that serves broad public priorities, addresses market failures by funding research that the private sector does not and cannot, and generates virtuous cycles that encourage public and private sectors alike to further invest in research and innovation.

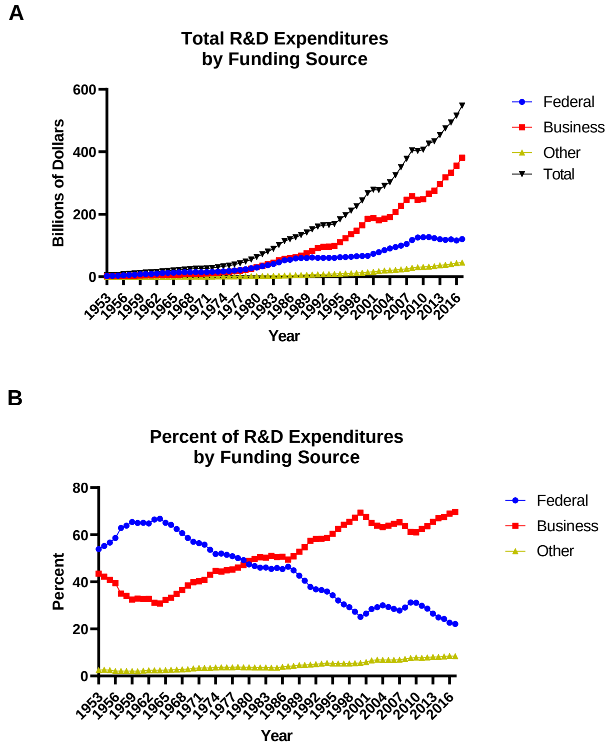

Figure 2: The private sector has overtaken the federal government in research development (R&D) spending. (A) Total R&D expenditures by funding source, in billions of dollars. (B) Percentage of total US R&D funding from the federal government, businesses, and other sources. All amounts are in current U.S. dollars. Source: National Science Board, National Science Foundation, 2020, Research and Development: U.S. Trends and International Comparisons, Science and Engineering Indicators 2020, NSB-2020-3, Alexandria, VA. Available at https://ncses.nsf.gov/pubs/nsb20203/.

Classification of R&D

The government often classifies research into three categories: basic research, applied research, and development (see Fig. 3 for official definitions). This linear model of innovation wherein knowledge is generated from basic research, then expanded towards some practical use in applied research, and finally formalized into some technology during development only captures the first role of federal funding which is to address the lack of industry support of fundamental research. This model was enshrined in modern science policy by Vannevar Bush's report *Science, the Endless Frontier*. Bush was the Dean of the MIT School of Engineering and head of the Office of Scientific Research and Development during World War II; his report is widely seen has having defined America's post-WWII research enterprise [16]. This linear model of innovation is increasingly understood to be overly simplistic [17]. Even Bush noted in his report that there is no strict line between basic and applied research.

Basic Research	"Experimental or theoretical work undertaken primarily to acquire new knowledge of the underlying foundations of phenomena and observable facts, without any particular application or use in view"
Applied Research	"Original investigation undertaken to acquire new knowledge; directed primarily, however, toward a specific, practical aim or objective"
Experimental Development	"Systematic work, drawing on knowledge gained from research and practical experience and producing additional knowledge, which is directed to producing new products or processes or to improving existing products or processes"

Source: OECD, 2015

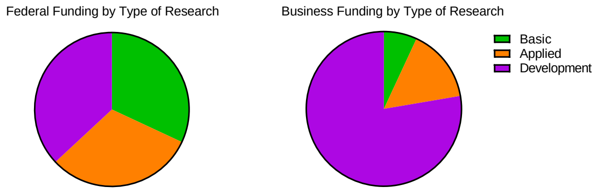

Figure 3: Comparing the type of research that the federal government and businesses fund. The table gives the definitions of basic, applied, and experimental development used by the National Science Foundation and National Science Board in the 2020 Science Indicators report. The pie charts show how much federal and private sector funding is devoted to each of these research categories. Source: National Science Board, National Science Foundation, 2020, Science and Engineering Indicators 2020: The State of U.S. Science and Engineering, NSB-2020-1, Alexandria, VA. Available at https://ncses.nsf.gov/pubs/nsb20201/.

The problem, however, is not just an ambiguous boundary between basic and applied work, but also the idea that the generation of fundamental knowledge of nature is strictly correlated with a purity of intent free of practical considerations. Indeed, there is a misconception that basic research corresponds to "pure" research [18]. A more realistic categorization of research uses the criteria of whether or not its intent is to generate fundamental knowledge and whether or not there was some practical motivation behind the work; such a categorization encapsulates both roles of federal research which are to support fundamental research and guide innovation toward societal needs. These criteria are not redundant, and "basic" research that generates knowledge can also be motivated by use. Donald Stokes, a renowned political scientist and previous dean of the Princeton School of Public and International Affairs, gives a more nuanced model in which research is split into four quadrants based on these two criteria of knowledge generation and use (Fig. 4) [19, 20]. Canonical examples of the quadrants would be Niels Bohr's work on atomic structure which was motivated purely by a quest for understanding without use, Thomas Edison's pursuit of electrical lighting which was motivated purely by use without a desire for fundamental knowledge, and Louis Pasteur's work on germ theory which was motivated by both the desire for knowledge and practical use. The fourth quadrant of work which is motivated neither by practical

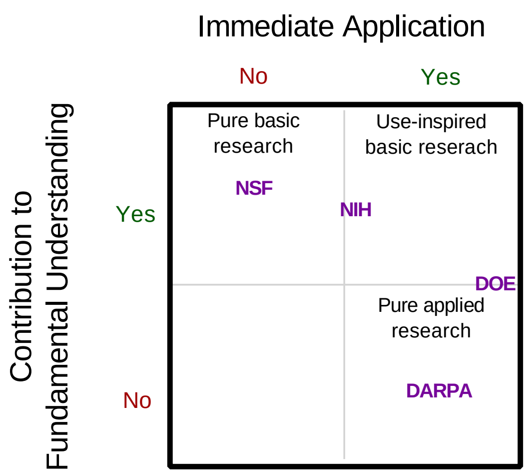

Figure 4: Quadrant model of federal R&D funding. Funding sources are categorized by proximity to application and contribution to fundamental understanding.

use nor fundamental knowledge consists, for example, of taxonomic or classificatory research and tinkering projects [19].

This quadrant model also better captures the complex relationship between science and technological innovation. Knowledge generated from scientific inquiry can certainly lead to new and improved technologies, however, the invention of some piece of technology often motivates basic research to investigate the natural phenomenon underpinning the device. A modern example is the complicated web connecting high-temperature superconductivity, magnets in MRI machines, nuclear fusion reactors, and efforts to design quantum computers and simulators; these seemingly disparate fields of science and technology have intimately connected motivations that flow back and forth between fundamental science and societally relevant technologies.

Funding Public Priorities

The intent to connect the government's R&D expenditure to societal needs has been expressed by administrations across the political spectrum [21, 22]. The role of federal funding in supporting fundamental research and in addressing societal needs can thus be accommodated by framing the U.S. government's approach to science through the lens of use-inspired research. Such a compact meshes naturally with the missions of agencies which disperse federal funds and makes it more natural to justify public investment of science broadly, including investment in pure undirected research through its support of use-inspired research, motivated by an application, and ultimately technological progress [19]. The majority of federal R&D funding is distributed by the National Institutes of Health (NIH), National Science Foundation (NSF), Department of Defense (DoD), and Department of Energy (DOE), with over 60% of funds going to university-based academics, who are the primary contributors of fundamental research [23]. These agencies have a variety of different missions that address different societal needs. For example, the NIH's mission is to improve human health through the scientific understanding of disease and health, the NSF's mission includes general scientific learning and discovery, DARPA (part of the DoD) focuses on technologies related to national security, and ARPA-E (part of the DOE) focuses on energy technologies. In line with their driving purposes, these agencies fund a spectrum of research across the various quadrants in Stokes's model (Fig. 4).

We see, however, that the overall portfolio of federal funding broadly centers around the quadrant of use-inspired basic research, with support in adjacent quadrants providing the healthy environment required for such use-inspired research to thrive; the complex interplay between science and technology means that research in one quadrant often depends on progress in others. When the "use" in the use-inspired research is contextualized towards societal needs through the missions of government agencies, the use-inspired research becomes societally relevant research. The federal government's broad focus on societally relevant research does not hinder academic freedom at the project level; government funding agencies keep broad societally relevant use cases in mind when forming their grant portfolio, but scientists undertaking research through individual grants still have the leeway to be undirected in their intent. In this way, there is a notion of national welfare underpinning public research funding while scientists remain largely uninfluenced by this context in their pursuit of knowledge. Such a compact between science and the government gives a stronger argument for funding science than the pure notion of science as a public good. Federal R&D funding therefore plays the critical role of generating research relevant to public priorities such as healthcare and a clean environment which are at the core of the missions of federal agencies. As will be discussed in the following sections, this research not only provides the bedrock upon which industry R&D is done, but also creates a "crowd-in" effect by which other parts of the national innovation infrastructure invest in areas related to these public priorities.

Addressing Market Failures

Unlike the private sector, the federal government is uniquely suited to guide national innovation toward public priorities, such as healthcare, clean energy, and infrastructure, that market incentives ignore [24]. The government has a role in two different types of market failure. The first is a true market failure where fundamental research underlying new technologies is not funded by the private sector due to the risk-reward profile and timeline to commercial relevance. The second is that regardless of how efficient the market is, an incrementally progressing economy does not always align with pressing societal needs or generate optimal societal outcomes.

Private firms' and industries' goal to maximize profit from an R&D investment often results in the financing of short-term, low-risk technologies. This is especially true in areas where the foundational research is mostly complete and the bulk of the remaining work is in short-term development. It follows that U.S. industries tend to spend about 80% of their R&D investments on technological development and only 20% on foundational research, which are longer-term, riskier (although arguably cheaper) investments [8]. This trend towards "short-termism" has become increasingly predominant in industry with more and more investment going into development rather than research [25]. As less and less research is being done in the private sector, companies are increasingly relying on work done at academic institutions funded by the federal government. For example, almost 90% of high-impact research papers authored by corporations were written in collaboration with scientists at academic and government labs [26]. The amount of corporate patents that rely on work done elsewhere has also increased dramatically; almost a third of all patents filed in recent years cite federally-supported research. The patents that cite federally-supported research were also found to be of greater substance and novelty on average [27].

While the reliance of the private sector on research produced elsewhere is not problematic *a priori*, this model only works when federal funding is available to provide these long-term, risky investments into basic and applied research. For example, the U.S. shale gas boom relied heavily on federal funding through the scientific research performed at the Gas Research Institute and the geologic mapping technology developed at Sandia National Labs [24]. This is an example of the federal funding addressing a true market failure by derisking private sector R&D.

The market by itself, however, is often blind to environmental concerns and the long-run societal and economic impact of pressing issues like climate change. Such societal issues are the purview of the federal government, which can use federal funding and other policies to catalyze national innovation towards clean energy technologies and climate resilience. Other examples of public priorities where the government has a pivotal role include developing new antibiotics and understanding the effects of opioids [28]–[30]. Federal research funding is therefore critical both by supporting fundamental research that the private sector is not incentivized to invest in, as well as by providing leadership in targeting societally critical issues. Below, we give two case studies demonstrating these roles.

Case study 1: A canonical example of the government's role in laying the foundation for innovative technology is the Internet. While the concept of a wireless telecommunications system was around as far back as the early 1900s when Nikola Tesla coined the term "World Wireless System," the first working prototype of such a network was created by the Department of Defense under the Advanced Research Projects Agency (ARPA) [31]. The goal of "ARPANET," as it was named, was to create a secure telecommunications system that could distribute information wirelessly in the case of an attack [32]. ARPANET incorporated many key innovations including the concept of "packet switching"—breaking an electronic message into smaller packages that can be transmitted to a new location and re-assembled. The initial network had host computers connected via phone lines to "interface message processors"—the predecessor to the modern-day router [32]. Over the next 20 years, ARPA-funded researchers continued to develop advanced communication protocols and to expand ARPANET into a broader "network of networks" [31, 33]. In addition to the role of ARPA, another federal agency, the National Science Foundation (NSF), was also essential in providing networking services and high-end computing power to universities across the county. These NSF-supported supercomputing centers developed many advances in web applications, including the first freely accessible web browser, which was the basis of modern browsers including Microsoft Internet Explorer and Netscape Navigator [34]. While the Internet as it is known today cannot be credited to any single organization, the role of government research in laying the foundation is undeniable. It is difficult to imagine that such an expansive project involving years of research and coordination across multiple institutes could have been undertaken without its involvement [35].

Case study 2: A good example of the mismatch of public and private objectives can be seen in the development of new antibiotics to keep ahead of rising bacterial resistance to pre-existing drugs. Antimicrobial resistance is widely recognized as one of the greatest threats of the 21st century [36]. Widespread use of antibiotics has led to the evolution of drug-resistant bacteria that no longer respond to currently used treatment methods. Thus, there is a critical need to produce new antibiotics. In spite of this, there has actually been a decrease in the number of new antibiotics being developed and approved since the 1980s, and many large pharmaceutical companies have downsized or eliminated their antibiotic discovery programs [37, 38]. This is because there are several barriers that limit the profitability of new antibiotics, often leading to a poor return on investment. Unlike drugs for chronic conditions, antibiotics are typically taken for a short period of time. New antibiotics entering the market face competition from cheaper generics, and are often reserved as drugs of last resort [39]. Even if an antibiotic is successful, there is always a danger that resistance to the new drug will emerge, so it may only be effective for a limited window of time.

Given the high risk associated with bringing any new drug to market and limited ability to recoup investments, it is understandable that this is a priority that the private sector will not address on its own. Thus, several government agencies have stepped in to fill the gap. For example, the Biomedical Advanced Research and Development Authority (BARDA) has contributed $1.1 billion since 2010, advancing nine new antibiotics to clinical development, three of which have already been approved [29]. BARDA and several other Department of Health and Human Services (HHS) agencies have also awarded grants and facilitated public-private partnerships to incentivize the development of new drug candidates [39, 40]. It is clear that without continued federal involvement, there would exist few solutions against a post-antibiotic world where millions die each year from bacterial infections that were once easily treatable [36].

Virtuous Cycles of Federal Funding

In addition to directly supporting research related to public priorities, federal investment also produces a domino effect in resource commitment, inducing investment from non-federal sources such as the private and philanthropic sectors into R&D related to broad societal objectives [41]. A multitude of studies have found that government investment in R&D increases private investment and effort (see, for example, [42]). Analysis done by Lanahan et al. in 2016 estimated that every 1% increase in federal research funding leads to a 0.468% increase in industry research investment, a 0.411% increase in nonprofit research investment, and a 0.217% increase in state and local research funding, cumulatively more than doubling the initial federal investment [41]. This positive feedback effect generally holds true across different disciplines including life sciences, physical sciences, and engineering. We therefore see that federal funding has an effect of "crowding-in" R&D investment from non-federal sources rather than crowding them out, as is sometimes erroneously assumed. As federal R&D investments are typically made in line with the missions of federal agencies which are in line with public priorities, increasing federal funding would lead the entire national R&D infrastructure to move more in step with societal needs and public benefits rather than purely market considerations. Additionally, federally-supported research is much more likely to be publicly disclosed compared to private sector R&D, and is therefore more likely to catalyze other innovations [23]. For example, as previously discussed, advances in supercomputing, and even the invention of the web browser, were built upon research done on computationally modeling black hole collisions [43]. As another example, fundamental physics research studying the movement of atoms led to the invention of molecular resonance imaging (MRI), a medical technology that helps save countless lives today [44, 45].

Federal R&D expenditure is also responsible for both the education and training of scientists and engineers who move into the broader workforce as well as the physical infrastructure that often forms the kernel for regional hubs of technological innovation [46]. A core part of the NSF's mission, for example, is supporting science, technology, engineering, and mathematics (STEM) education and the broader development of the human capital pipeline for national R&D [23]. The agency is also tasked with maintenance of large-scale research infrastructure such as facilities for materials research and fabrication, high-performance computing facilities, and particle accelerators, out of which technologies underlying countless start-ups and private sector innovations have been born [47]. The work done by university research centers and national labs, both of which are primarily funded by the federal government, also end up attracting technology incubators, start-ups, and a larger industry presence [3]. Therefore, federal funding is often responsible for the key centers around which technology hubs form and lead to regional economic growth; examples include Silicon Valley in California; Boston, Massachusetts; the Research Triangle Park in North Carolina; the Boulder-Denver corridor in Colorado; and Madison, Wisconsin. In addition to its indirect role in forming such innovation hubs, the federal government often takes a direct role in creating infrastructure critical to future private sector R&D including advanced manufacturing, high-performance computing, and smart cities [48]. Federal funding, therefore, plays two major roles: it spurs the general pace of national innovation forward, and it guides the national innovation ecosystem towards societal priorities. Both of these tasks are accomplished by utilizing the "crowd-in" effect of federal R&D investments, the training of the STEM workforce, the tendency for technology hubs to form around academic and federal research centers, and the types of R&D infrastructure the government catalyzes.

Proposals

In this paper, we have shown that federal investment in R&D is stagnant at best and, by some measures, declining. We also provide theoretical context and case studies illustrating why federal funding is uniquely important to creating innovations in research that benefit the public good. Here, we provide proposals for how to translate this message to the public in order to effect political change. We recognize that these proposals alone will not be sufficient if the goal is to bolster federal research funding; such an endeavor will certainly require a broad array of approaches, including the utilization of professional advocacy efforts and a discussion of the budgetary mechanisms that could be used to increase or reallocate federal discretionary funds. However, in this section, we focus on public advocacy as a necessary and often overlooked strategy that can safeguard grassroots political support for federal funding into the future.

This focus on public engagement is particularly salient in light of an increasingly visible "science–public divide," a phenomenon whereby growing segments of the public are embracing views that are contrary to scientific consensus, such as the anti-vaccine movement [49]. The current COVID-19 epidemic also highlights how failures in communication can have important public health consequences [50]. Evidence to be discussed below indicates that while public support for science is still generally strong, Americans are somewhat disconnected from the world of science itself. There are dire consequences caused by rifts between "elite, ivory-tower scientists" and "everyone else." Science is a collective national and societal endeavor, and only by keeping it so can there be sustained public support for science. The discussion that follows lays out recommendations for safeguarding the close, symbiotic relationship between the scientific community and the general public.

As we have discussed, the federal government plays an integral role in translating scientific research into technologies and solutions that impact our everyday lives. We believe that this is an important message to convey to both policymakers and the public to galvanize support for federal R&D funding. The American public must understand that America's scientific and technological breakthroughs are not merely badges of national prestige; they have material impacts on our standard of living and our national security. While most Americans agree that the federal government should fund scientific research, less than half support increasing federal R&D funding [51]. This issue is likely compounded by the fact that the majority of Americans overestimate the amount of government spending that is devoted to scientific research relative to other priorities [52]. Additionally, in a public survey from 2011, when adults in the U.S. were asked the question "Which one of the following domestic programs would you be willing to cut government spending in order to reduce the federal deficit?", scientific research was at the top of the list [53].

By reframing the discussion around the role of federal R&D funding, we hope to change public opinion. Recent public survey data from the organization ScienceCounts, an organization dedicated to increasing public awareness and support for scientific research, examined the type of science that Americans believe various institutions do best. According to ScienceCounts, the American public believes that the private sector is best at creating new processes and products and driving economic growth. By contrast, Americans believe that universities, which are largely federally-funded, are best at discovering how things work [54]. This survey data suggests that Americans are unaware of how many federal dollars go towards use-inspired research, and how integral federal funding is to the accomplishment of public priorities, the pursuit of innovative moonshot initiatives, and the R&D ecosystem as a whole. Even if the public is not explicitly aware of the linear model of scientific research, it seems to largely view research progress through this lens. We believe that this finding helps to explain why only one in four people believe government funding of scientific research is essential [15].

The good news is that Americans have an overall positive view of science and are optimistic about how science can be used to improve society. Almost all (92%) of the public agreed that science and technology create "more opportunities for the next generation" [51]. Importantly, one of the major findings of the ScienceCounts research is that the primary association that people have with science is hope—a powerful brand that can and should be utilized by science advocates [15].

The above review of public perceptions of science suggests an enormous opportunity. If the public can be persuaded that federal R&D funding is uniquely important to actualize those aspirational hopes that science promises, this would go a long way towards increasing public engagement and support for federally-funded science. We believe that citizen-level involvement is a powerful and under-recognized strategy for enacting political change. Here, we outline three steps necessary to achieve this public advocacy goal.

1) **Identifying specific scientific outcomes the public prioritizes.** It is wonderful news that people so strongly associate scientific research with hope, but what exactly is it that people are hoping for? In a pilot digital marketing-based study, ScienceCounts found that general messages of hope do not work, finding that "in the absence of a clear benefit, the promise of science becomes weak and generic, losing much of its appeal" [53]. We propose conducting research to better understand what exactly it is the public values and cares about most. What diseases do people most want to see cured? What environmental concerns do people believe are most pressing? What advances in computing and information technology are people most excited about? Are these values uniform, or are there differences among various segments of the population? Such information would empower science advocates to effectively cater their efforts, and to draw concrete connections to how science can benefit people personally and improve their daily lives.
2) **Developing and supporting effective public communication efforts in the scientific community.** Once science advocates identify *what* specific messages will resonate with the public, they need to consider *how* to most effectively convey them. Research suggests that piquing people's interest and curiosity should be a key goal of science communication [55], with one

study noting that people's level of scientific interest influences how much they support public research funding [56]. There is also a growing body of literature on the power of narrative storytelling for communicating science. Contextualizing messages within a narrative helps audiences comprehend and recall information, fosters interest and emotional connection, and when done well, is a very effective way to persuade audiences [57]–[59]. Thus, we propose that science advocates work to develop compelling narrative describing examples of scientific discoveries that have had a positive impact on people's lives. An example would be the Golden Goose Awards, which highlight scientific research that seems strange or obscure, but which has reaped unexpected societal benefits [60].

In order to convey these messages to the public, stakeholders—namely scientists and the science-interested public—need to be trained in how to communicate effectively. Survey data suggests that there is a high level of willingness and interest among scientists to engage with the public [61, 62]. There has also been an increase in graduate-level training and professional development opportunities in science communication [63]. We believe that such opportunities for training should continue to be expanded. However, several studies have reported that lack of institutional support remains a barrier to engagement efforts [63, 64]. Thus we also propose that university leaders should place higher value on science communication. Funding agencies could also facilitate this by providing incentives for scientific grant holders to participate in public communication efforts.

3) **Mobilizing the public as advocates to safeguard the American research enterprise.** As it stands, scientists are not very visible to the public eye. A 2019 survey by Research!America found that only 20% of Americans can name a living scientist [65] [1]. By increasing the amount of engagement that scientists have with the public, scientific stakeholders can energize and excite people about the benefits of scientific research. This matters because the public are also constituents. A report from the Congressional Management Foundation found that, perhaps contrary to popular perception, interactions with constituents have considerable influence on policymakers' decisions [66]. By pairing scientific communication with a call for increased support of federal research funding, we can thus galvanize a largely-untapped base of grassroots political support for this important issue. We certainly believe that direct advocacy by scientists and scientific societies to policymakers is important, and we expect that the above recommendations about communication will apply to policymakers as much as the general public. Concretely, there are many different forms that these efforts can take, from local grassroots outreach events to nation-wide advertising and public relations campaigns. Ultimately, we contend that we can increase the power of our advocacy by mobilizing broader segments of the general public to also speak up and be a voice for science.

[1] We recognize that the current COVID-19 pandemic has dramatically increased the visibility of science both in the United States and worldwide. Certainly, scientists like Dr. Anthony Fauci and Dr. Deborah Birx have become household names in recent months. It will certainly be interesting to see how this impacts the perception and support of science broadly over a longer time-span, although such a discussion is beyond the scope of this article.

Conclusion

As the world continues on a path of ever-more-rapid technological change, we believe that it is critical for the United States to remain a leader in progressing science, technology, and innovation to improve the human condition and to expand the frontiers of discovery. People have long looked to scientific and technological advances to improve their way of life, and to create solutions that address pressing societal needs. Especially in an era of increasingly prevalent public health and climate crises, it is critical that we restore the integrity of our national innovation infrastructure.

Acknowledgements

The authors would like to thank Rebecca J. Chmiel for her contributions and thoughtful discussions.

Citation

Mandt, R., Seetharam, K. & Cheng, C. H. M. Federal R&D funding: the bedrock of national innovation. *MIT Science Policy Review* **1**, 44-54 (2020).

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