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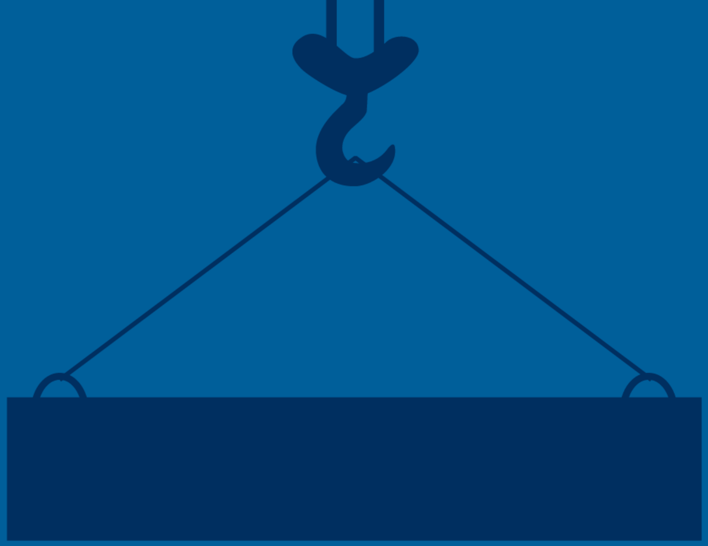

CHAPTER

Science and Innovation: The Under-Fueled Engine of Prosperity

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Science and Innovation: The Under-Fueled Engine of Prosperity

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ABSTRACT

Science and innovation are central to human progress and national economic success. Currently, the United States invests 2.8% of GDP in research and development, which is supported by a range of public policies. This chapter asks whether the United States invests enough. To answer that question, the conceptual case for government intervention and skepticism about that case are reviewed. The chapter then turns to systematic evidence, including the very latest evidence, regarding the operation of the science and innovation system and its social returns. This evidence suggests a clear answer: We massively underinvest in science and innovation, with implications for our standards of living, health, national competitiveness, and capacity to respond to crisis.

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1. Introduction

Scientific and technological advances have long been recognized as engines of economic growth and rising prosperity. The fruits of these advances—instantaneous global communications, vaccines, airplanes, heart surgery, computers, skyscrapers, industrial robots, on-demand entertainment, to name a few—might seem almost magical to our ancestors from not-too-many generations ago. The power of this progress has been broadly evident since the Industrial Revolution and was recognized at the time, including by political leaders. As the British Prime Minister Benjamin Disraeli noted in 1873, "How much has happened in these fifty years … I am thinking of those revolutions of science which … have changed the position and prospects of mankind more than all the conquests and all the codes and all the legislators that ever lived."

Disraeli was talking of things like the steam engine, the telegraph, and textile manufacturing. In the century and a half since Disraeli's observation, standards of living have advanced remarkably amidst the continued progress of science and technology. Real income per-capita in the United States is 18 times larger today than it was in 1870 (Jones 2016). These gains follow from massive increases in productivity. For example, U.S. corn farmers produce 12 times the farm output per hour since just 1950 (Fuglie et al. 2007; USDA 2020). Better biology (seeds, genetic engineering), chemistry (fertilizers, pesticides), and machinery (tractors, combine harvesters) have revolutionized agricultural productivity (Alston and Pardey 2021), to the point that in 2018 a single combine harvester, operating on a farm in Illinois, harvested 3.5 million pounds of corn in just 12 hours (CLASS, n.d.). In 1850, it took five months in a covered wagon to travel west from Missouri to Oregon and California, but today it can be done in five hours—traveling seven miles up in the sky. Today, people carry smartphones that are computationally more powerful than a 1980s-era Cray II supercomputer, allowing an array of previously hard-to-imagine things—such as conducting a video call with distant family members while riding in the back of a car that was hailed using GPS satellites overhead.

Improvements in health are also striking: Life expectancy has increased by 35 years since the late 19th century, when about one in five children born did not reach their first birthday (Murphy and Topel 2000). Back then, typhoid, cholera, and other diseases ran rampant, Louis Pasteur had just formulated the germ theory of disease, which struggled to gain acceptance, and antibiotics did not exist. In the 1880s, even for those who managed to reach age 10, U.S. life expectancy was just age 48 (Costa 2015). Overall, when examining health and longevity, real income, or the rising productivity in agriculture, transportation, manufacturing, and other sectors of the economy, the central roles of scientific and technological progress are readily apparent and repeatedly affirmed (Mokyr 1990; Solow 1956; Cutler et al. 2006; Alston and Pardey 2021; Waldfogel 2021).

But the stakes in science and innovation go beyond the longer-run rise of economic prosperity and health. Science and innovation are also central to confronting emergent threats. The COVID-19 pandemic, and the key role that novel vaccines have played in the U.S. recovery, demonstrate the importance of science and innovation to national resilience. Similarly, rapid scientific and technological advances were key to U.S. success in World War II (Snow 1959; Gross and Sampat 2020). Indeed, keeping ahead of one's adversaries through science and technology has long been recognized as central to national defense (Bush 1945; NAS 2007; Center and Bates 2019). Whether facing a pandemic, climate change, cybersecurity threats, outright conflict, or other challenges, a robust capacity to innovate—and to do so quickly—appears central to national security and national resilience.

Further, in a globalized world, workers compete in a global context. The productivity and comparative advantage of a nation's workforce depend on the advanced tools and skills that a nation can bring to its production. Innovation is thus key to creating high-paying jobs and maintaining national economic leadership, a benefit that the United States and its workforce have long enjoyed. And to the extent that systems of government depend on the visible success of the nation's economic models, U.S. scientific and technological progress have supported the attractiveness and durability of democracy and free market systems, playing a key role in resolving the Cold War in favor of liberty and facing new competition with authoritarian systems like China (Shirk et al. 2020). As with national security, the position of the U.S. economy in a global landscape hinges on keeping ahead—on continual progress in science and technology. Ultimately, scientific and technological advance not only drive improved standards of living and longer and healthier lives, but these advances underpin national economic success, national security, and the attractiveness of the national model.

These perspectives all point to the central role of science and innovation in the national interest. At the same time, there is a distinction between recognizing the deep contributions of science and innovation and saying that *government and public policy* have big roles to play in driving science and innovation. The purpose of this chapter is to focus precisely on this case. What is the case for a substantial government role in science and innovation? What is the evidence? How are we doing? What policy changes do we need? In answering these questions, the available evidence, including the very latest evidence, will suggest important answers. Namely, based on what we know now, the United States (and the world) appear to greatly underinvest in science and innovation. Investing in science and innovation is perhaps the world's greatest market failure and policy changes will be essential to doing more.

This chapter proceeds in three parts. First, it considers the role of science and innovation as "public goods," the conceptual basis for understanding why private markets underinvest in science and innovation and why there is an essential role for public action. At the same time, this chapter directly engages common forms of public skepticism about the value of scientific research, including the view that science may be isolated from the broader public interest and the issue that science and innovation investments often fail. These perspectives are laid out in Section 2 together with the usual kinds of anecdotal evidence that are used to illuminate them. Section 3 then turns to systematic evidence, drawing in the latest findings to see what is true in general, as opposed to in isolated anecdotes. This section argues that, when examined in light of systematic empirical evidence, there is a clear case for strengthening public support. Finally, Section 4 considers policy innovations that can bring the United States greater scientific and technological success—to create higher standards of living, longer and healthier lives, an increasingly competitive workforce, a more resilient nation, and a more effective model for the world. Section 5 concludes.

2. Science and innovation policy: public goods and public skeptics

Why should government and public policy have an important role to play in encouraging scientific and technological progress? The case hinges on the idea that the market, left to itself, provides insufficient incentive to invest in new ideas and thus underinvests in science and innovation. This perspective in turn motivates an array of approaches where public policy may work to increase science and innovation investments in line with their social value. This section will first lay out these conceptual arguments, with examples. Several forms of skepticism about science and innovation policy are then considered, also with examples. Systematic evidence will be considered in the following sections.

2.a. Science and innovation as a public good

Markets may function efficiently for the production of many ordinary goods and services. But the outputs of science and innovation are not ordinary goods. The outputs are, at root, new ideas: new knowledge and ways of doing things. And ideas have unusual properties. As Thomas Jefferson once observed, "He who receives an idea from me, receives instruction himself without lessening mine; as he who lights his taper at mine, receives light without darkening me." Jefferson is observing that an idea, once it is created, can bring benefit not just to the creator but to many additional parties—it can light other candles, creating benefits far beyond that first candle's light. When Isaac Newton discovered calculus, or Henry Ford introduced the assembly line, or Emmanuelle Charpentier and Jennifer Doudna developed the gene-editing tool CRISPR, they shined a new light on the world, a light that others could use.

This potential for broader use elevates the social value of ideas. Yet the value in this broader use may be difficult for the initial innovator to capture. Rather, the benefits from that spreading light may be largely captured by others. For example, others may use the exact same discovery, tool, or idea—say, calculus, the structure of DNA, or a machine-learning algorithm. Others may similarly use the original idea as inspiration for distinct variants—electric vehicles, mRNA-based vaccines, or cloud-based computing services. With the advance of ideas, some party engages in costly and risky work to discover or develop a new idea. Then, inspired by the original innovator, the social value spreads to many other parties. To the extent that the original creator does not capture this broader social value, the private value can fall short of the social value it creates. Then the private incentives to invest in creating the idea may be well below the social interest in making that investment. This is the basic market failure, and incentive problem, that surrounds the advance of ideas.

Beyond more immediate imitative spillovers, additional social value comes over time, where one advance unlocks doorways to further scientific or technological progress. These so-called “intertemporal spillovers” can be both valuable and unpredictable—and difficult for the initial innovator to capture. Examples in marketplace innovation include the personal computer, Internet, or smartphone, the creation of which opened the doorway to enormous arrays of novel software applications and business models. Intertemporal spillovers are also particularly germane in science. In science, an advance typically has no direct marketplace application but rather is a step forward in the deeper understanding of nature. Yet this deeper understanding of nature may prove essential to future marketplace innovation. Vannevar Bush, who led the U.S. science and technology efforts in World War II, evocatively described science along these lines as “the fund from which the practical applications of knowledge must be drawn” (Bush 1945).

To illuminate such spillovers concretely in today’s context, consider two examples. The first concerns the relationship between Uber and Albert Einstein. Uber is a novel business model that has disrupted the transportation sector, and to the user Uber might appear as a simple mobile app enabling a new business idea. But Uber relies on a string of prior scientific achievements. Among them is GPS technology, embedded in the smartphone and in satellites overhead, which allows the driver and rider to match and meet. The GPS system in turn works by comparing extremely accurate time signals from atomic clocks on the satellites. But because the satellites are moving at high velocity compared to app users and experience less gravity, time is ticking at a different speed on the satellites, according to Einstein’s mind-bending theories of special and general relativity. In practice, the atomic clocks are adjusted according to Einstein’s equations, before the satellite is launched, to account exactly for these relativistic effects. Without these corrections, the system would not work. There is thus a series of intertemporal spillovers from Einstein to the GPS system to the smartphone to Uber (not to mention all the other innovations, mobile applications, and new businesses that rely on GPS technology).

As another example, consider the modern biotechnology industry and its many applications—genetic testing, cancer diagnosis, gene-based drug development, paternity tests, criminal forensics, testing for COVID-19, etc.—that depend on the analysis of DNA. To study DNA, it must first be replicated into measurable quantities, and this replication process depends on many prior scientific advances. One critical if unexpected advance occurred in 1969, when two University of Indiana biologists, Thomas Brock and Hudson Freeze, were exploring hot springs in Yellowstone National Park. Brock and Freeze were asking a simple question: can life exist in such hot environments? They discovered a bacterium that not only survived but thrived—a so-called extremophile organism—which they named *Thermus aquaticus*. Like Einstein's work on relativity, this type of scientific inquiry was motivated by a desire for a deeper understanding of nature, and it had no obvious or immediate application. However, in the 1980s, Kary Mullis at the Cetus Corporation was searching for an enzyme that could efficiently replicate human DNA. Such replication faces a deep challenge: it needs to be conducted at high heat, where the DNA unwinds and can be copied, but at high heat replication enzymes do not hold together. Mullis, in a Eureka moment, recalled the story of *Thermus aquaticus*, knowing that this little bacterium must be able to replicate its DNA at high heat given its environment. And indeed, *Thermus aquaticus* turned out to provide what was needed. Its replication enzyme was declared by *Science Magazine* to be the "molecule of the year" in 1989. Mullis would be awarded a Nobel Prize soon after, and the biotechnology industry would boom, opening new chapters of human progress.

These examples highlight several features that we will return to later with systematic evidence. First, we see essential roles that science can play in enabling marketplace innovations. Second, we see that the spillovers from science can be highly unpredictable. Finally, we see a key limitation of market-based investment incentives in the context of new ideas. Namely, the market value of Einstein's insights or Brock and Freeze's discoveries are essentially zero—there is no marketable product or service that they directly provide, and markets not surprisingly provided no funding for their research. Yet their discoveries form foundations for entire industries. Even when there is a marketable product or service, such as Mullis's DNA replication approach, the imitative and intertemporal spillovers that follow suggest that the private returns captured by the initial innovator can be much lower than the social value created.[1]

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[1] Indeed, Kary Mullis and the Cetus Corporation would receive a tiny sliver of the social value enabled by their advance.

In a modern context, economists recognize Jefferson's candle, where the light of one candle becomes the light of many, as defining an aptly named "public good."[2] In general, public policy can play key roles in the provision of such goods. In the context of idea production, policy interventions take many forms—government-sponsored research funding, intellectual property systems, research and development (R&D) tax credits, prizes, public research contracts, demand-side "pull" mechanisms like advanced purchase commitments, and others. All of these approaches seek to encourage the advance of ideas, recognizing the high social returns that may greatly exceed the private returns. In each case, these policies attempt to repair relatively weak incentives in markets to produce new ideas, and bring greater resources to these efforts, in line with the social returns.

2.b. Science and innovation as a stumble in the dark

While the value of an effective new idea, once it is in hand, may be high, a different perspective emphasizes how hard it is to light the first candle. Discovering an important new insight about nature or creating a valuable new product or service is difficult, and investments in science and innovation by nature have unclear prospects. They are steps into the unknown, with results that are fundamentally uncertain (Arrow 1962). The image of light spreading from one candle to another happens later in the process. The actual, up-front activity of science and innovation is more like a stumble in the dark, searching for a light that may or may not be there.

This fundamental uncertainty means not only that the right direction for investment is not obvious, but also that failure is common. Well-intended investments fail to produce value, and experts often make incorrect bets. In science, many research projects are abandoned and those seen through have widely varying impact (de Solla Price 1965; Yin et al. 2019). Beyond individual projects, larger streams of research can fail. The same scientist can see great success in one agenda and little or no success with another (Liu et al. 2018). Even Nobel Prize–winning researchers regularly produce failed work streams.[3]

With intertemporal spillovers, judging success and failure is even more difficult. Even when the idea is in hand, there is enormous uncertainty about its future prospects, and eventual success is often preceded by apparent failure. For example, although the science has been advancing since the 1990s, mRNA-based medication had faced a litany of failures—for cancer treatment, heart disease, kidney disease, and other

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[2] These are goods with two features: first, many people may benefit from it without impinging each other's use; and second, excluding people from its benefit is either difficult or undesirable. National security, public parks, and clean air are other examples of public goods.

[3] See https://www.nobelprize.org/failure/ for perspectives on failure from Nobel Prize winners themselves.

areas. At the start of 2020, no mRNA-based vaccine or drug treatment had ever been approved for use in humans. Yet mRNA vaccines proved extremely effective against COVID-19 and are now seen as a breakthrough in treating infectious disease, with renewed prospects for other diseases.[4] Scientists refer to specific ideas that are initially underappreciated as "sleeping beauties" (Ke et al. 2015), and sequential failures are often part of an iterative learning process that leads to eventual success (Yin et al. 2019).

Uncertainties and regular failure are not just common in basic research. They are common in marketplace innovation, too. In the pharmaceutical industry, a survey of the top 10 pharmaceutical firms found that only one in nine new compounds that reached human testing were ultimately approved for use (Kola and Landis 2004). In other words, leading pharmaceutical firms fail the vast majority of the time. Venture capitalists also fail. Consider Bessemer Venture Partners, a prominent and successful venture capital firm. In an exercise of public humility, Bessemer maintains an "anti-portfolio" on its website, noting all the new ventures that it reviewed and decided *not* to invest in. These missed early opportunities include Apple, Airbnb, Facebook, FedEx, Google, Intel, and Zoom, to name a few. In a study of another venture capital firm, researchers examined the return on each investment made to its prospects as initially judged by the venture firm's partners (Kerr et al. 2014). These are private sector investors, investing their own money and making their best bets. Yet the partners had essentially zero predictive success across the portfolio of their investments. Ultimately, it appears that in science and innovation, nobody has a crystal ball.

While the inherent uncertainty in science and innovation investments means that they inevitably produce many disappointments, the fact of regular failure can also breed doubts about the benefits of these investments more generally. If success is rare, and failure common, the social returns imagined from the "public goods" perspectives may be heavily reduced. One form of skepticism may then simply be that science and innovation success stories are relatively few and that science and innovation is a poor investment overall.

Other forms of skepticism focus on the allocation of research funding. Most science funding, especially in basic research, comes from the federal government (*i.e.*, from taxpayers), and observers have questioned the capacity of government officials to identify and invest in good opportunities. C.P. Snow famously suggested a cultural

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[4] As another high-profile example, artificial intelligence research also had a long history of failures before recent breakthroughs. Machine learning and neural networks methods, which developed in fits and starts over many decades, were for long periods seen as unpromising (Minsky and Papert 1969; Wooldridge 2021). But these methods are now driving innovation across the U.S. economy and the world and are the subject of increasingly intense international competition.

disconnect between scientists and policymakers that disrupts good decision-making with regard to science (Snow 1959). The resulting view, and concern, is that the public funding of science and technology is not allocated in line with the public interest. In the U.S. government, Senator Proxmire's Golden Fleece Awards regularly called out questionable lines of publicly supported research (Hatfield 2006). More recently, Solyndra has been held up as an example of poor public investment choices in the more applied, marketplace context. The Nobel Prize–winning economist Milton Friedman once argued that the government was likely to make poor R&D investment choices and suggested that perhaps R&D investments should be left to the private sector (Kealey 2013).

Skepticism can also focus on scientists and experts themselves. Scientists and researchers are often depicted as living in an "ivory tower" (especially in universities), disengaged from the real world and a practical understanding of the world's problems. Amidst rising skepticism about experts in general (*e.g.,* Nichols 2017), scientists and their priorities can be viewed with doubt, and the fact that their projects and ideas regularly fail can fuel the sense that their expertise is not especially useful. Meanwhile, the public readily sees examples of very young individuals—with little initial experience or advanced education—starting companies that bring transformative innovations to the economy. Examples include a young Steve Jobs, Bill Gates, and Mark Zuckerberg. Amidst regular examples of failure, the tension between the seemingly remote world of scientists and technology researchers and the readily apparent success of young innovators can breed skepticism about the value of deep expertise and scientists themselves.

Ultimately, the fundamental uncertainty in science and innovation and the related regularity of failure engenders several forms of skepticism: about the overall returns to science and innovation investments; about the capacity of the public sector to allocate research dollars; and about who actually drives breakthroughs and the value of experts themselves. In these more skeptical perspectives, the advance of science and technology might still be seen as a public good, but if public agencies, universities, or scientists themselves are poor at investment in practice, perhaps the social returns that public policy aims for are not actually realized. And while anecdotes can be marshaled on all sides of these debates, they cannot be settled with stories. Assessing these perspectives requires systematic evidence and data. What is actually happening on average? Are the social returns to science and innovation investment high or low in practice? Is public research funding, and its allocation across fields, aligned with the public interest? Who drives the progress of science and marketplace innovation, and where do the big breakthroughs come from? The following section addresses these questions.

3. Science and innovation in practice: what the evidence says

This section collects systematic evidence, including the most recent evidence, regarding the value and operation of the science and innovation system in practice. Much recent work has been enabled by the methodological advances, as well as the revolution of "big data," which produces comprehensive views. These studies strengthen the empirical foundations for assessing the science and innovation system, and while there are still many gaps in our understanding, a number of striking facts and important insights have emerged.

This section focuses on three specific questions. First, is the United States overinvested or underinvested in science and innovation? Second, are public science investments allocated in a way that is commensurate with the public interest? Third, who drives breakthroughs in science and innovation? Answering these questions is central to policy questions of whether, how, and how much the United States could successfully scale the science and innovation system.

3.a. The social returns to R&D

The question of whether to invest more in science and innovation is essentially a question of estimating the social returns to these investments. If the social returns are high, meaning that the benefits are large compared to the costs, then additional investment will be worthwhile. One way to measure this is a "social benefit–cost ratio," which calculates how many dollars of benefit society receives per dollar of investment cost. If the benefit-cost ratio exceeds 1, so that \$1 of investment cost returns more than \$1 of social benefit, then innovation investments are worthwhile and, from society's point of view, more than pay for themselves. An alternative calculation is a rate of return measure, in percentage terms per annum, which can then be compared to rates of return per annum on other investments (e.g., stock market returns or other benchmarks). Researchers have studied many industries, and used many methods, to ascertain the social return to science and innovation investments. The outcome measure is usually the increase in value-added output or productivity in an industry and the cost is usually the expenditure on R&D. In studying *social* returns, researchers are working to find not just the value of the R&D investment to the investing party, but also the additional benefits or costs to other parties. The headline of these studies is that, while estimates vary, the social returns to investment in R&D tend to be remarkably large, and much larger than the private returns to R&D and to ordinary private investment returns in other contexts (Griliches 1958; Mansfield 1977; Hall et al. 2010). See Table 1. For example, reviewing hundreds of studies on agricultural R&D, Alston et al. (2000) and Evenson (2001) find that median social rates of return estimates are over 40%, an investment return that is many multiples of stock market returns or the interest rate on government bonds. Similarly, a review by Hall et al. (2010) examines dozens of studies of manufacturing and other industries and finds similarly large median social rates of return.

Table 1: The social returns to R&D

Study	Industry / Context	Social Rate of Return	Social Benefit-Cost Ratio
Alston et al. (2000)	Agriculture (review of 292 studies)	44% (median)	--
Mansfield et al. (1977) and Tewksbury et al. (1980)	Industrial Innovations (37 case studies)	71% (median)	--
Bloom et al. 2013	Publicly-traded firms, All industries	55%	--
Azoulay et al. 2019	Biomedical research from the NIH	--	> 3
Jones and Summers (2020)	Overall U.S. Economy: Baseline estimate Conservative estimate	67% 20%	13.3 5

Notes: This table summarizes estimates of the social return to R&D investment. The social benefit-cost ratio conveys the number of dollars in benefit per dollar invested, where a ratio greater than 1 indicates that the investment pays back more than it costs. The social rate of return can be compared to standard private rates of return, as a percentage gain per year. See also Hall et al. (2010) for a review of methodologies and results. Overall, using many methods, industries, and research contexts, the social returns to R&D appear extremely high, pointing to enormous un-reaped rewards from further R&D investment.

Despite this tendency to find high social returns, some doubts have remained about these calculations, for three reasons. First, what is true for the industry, technology area, or time frame studied may not be generalizable. One may be concerned that studies are often "picking winners," focusing on technology areas that we know have advanced successfully and thus may not be representative of overall returns. Second, the causal linkage between R&D investment and the following output or productivity gains can be difficult to establish. Third, spillovers are messy. It is very difficult to trace the imitative or intertemporal benefits from a given advance, and some spillover effects may impose costs on other parties, not benefits.[5] Studies

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[5] For example, the spillover benefits of widely used advances like electricity, computers, the Internet, or the Human Genome Project are difficult to enumerate and assess. The spillovers from such "general purpose technologies" would appear to be extremely positive. On the other hand, private R&D returns in a business context can also exceed the social return through "business stealing," where private investors do well in part by reallocating business from other firms to themselves. For example, if Amazon earns income selling books online, it succeeds in part at the expense of existing bookstores, and here the private return to Amazon investors may (on this dimension) exceed the return to society as a whole.

might either over-attribute broader benefits to a given innovation or perhaps fail to account for the spillovers in a complete way. Recent methodological advances have led to new insights that confront these challenges explicitly, and here we consider three recent studies that make important headway—and once again find extremely high returns.

The first study, Bloom et al. (2013), examines industrial R&D. The analysis is particularly focused on isolating the causal impact of R&D and estimating its spillovers within related industries. Methodological advances in this study are both a causal research design, based on how businesses respond to changes in federal and state R&D tax incentives, and an analysis that distinguishes between potential positive and negative spillovers among industry participants.[6] Netting out the spillovers, the analysis finds that industrial R&D has a social rate of return of 55%, which is several times the private return experienced by the investing firm. The findings imply not only enormous social benefits to industrial R&D but also that private R&D investment is very low compared to its benefits for society.

The second study, Azoulay et al. (2019), examines scientific investments in biomedicine. The analysis is notable for its focus on the linkage between upstream basic research and downstream marketplace application, and in isolating causal impacts. The authors use features of the National Institutes of Health (NIH) funding system to isolate quasi-random changes in the funding for particular biomedical science areas. They then trace the effect of this marginal funding on new scientific research and on later inventions that build on this research. The central finding is that $10 million in additional NIH funding in a given area leads eventually to an additional three private sector patents, including novel drugs. Looking purely at the private returns to these patents suggests that private value of the patents greatly exceeds the expenditure by the NIH. This paper further demonstrates the unexpected ways that science propels technological progress, as the additional NIH funding, directed at a particular disease area, is often taken up in patents targeting other applications.

The third study, Jones and Summers (2020), examines the social returns across the U.S. economy. Whereas most studies examine the returns to R&D investment in particular sectors, this study takes a broader and longer-run view. In particular, this study calculates an overall return to science and innovation investment in the United States, both by examining total R&D spending on the cost side and total, valued-added output gains on the benefit side. By looking at all R&D spending

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[6] The potentially negative spillovers are from business stealing, where the innovating firm takes business from product market rivals, while the potentially positive spillovers are on businesses that may not compete with the focal business but build on related technologies.

the method accounts for the costs of both successes and failures. By looking at the overall growth path of the economy, the method can incorporate and net out spillovers with an unusually broad view.[7]

Although the Jones and Summers methodology is quite different from other approaches, it once again points to very high social returns. In the baseline estimates, the social rate of return to R&D expenditure in the U.S. economy appears to exceed 50%. Put in perhaps more salient terms, the analysis indicates that $1 invested in innovation produces, conservatively, at least $5 in social benefits on average—and quite possibly $10 or even $20 in social benefits per $1 spent.

In sum, a consistent picture of high returns emerges from these studies. This is true not only across numerous settings, but also across a wide range of methods, including new studies that use increasingly sophisticated and diverse estimation approaches. Notably, these social returns are not just good: They are enormous. Effectively, the science and innovation system is akin to having a machine where society can put in $1 and get back $5 or more. If any business or household had such a machine, they would use it all the time. But this machine is society's. The gains from investment largely accrue to others—not so much to the specific person who puts the dollar into the machine. This brings us back to Jefferson's candle and the public goods nature of innovation. The spreading light of new ideas brings large benefits and pays for its costs many times over, but these exceptional benefits are not captured by the private investor. Public policy thus has essential roles to play in elevating these investments and realizing the returns.

The pandemic provides an additional and salient example of the high social returns to science and innovation investments. Operation Warp Speed sought to accelerate the invention, manufacture, and delivery of novel vaccines, with the goal of overcoming the enormous public health and economic consequences that the pandemic has imposed. This public investment cost approximately $25 billion (Gross and Sampat 2021), and it is not difficult to see that this cost appears very small compared to the benefits vaccines have brought in helping solve the pandemic, whether the benefits are measured in lives saved or in the rekindling of economic activity.[8] Indeed, if all

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[7] For example, the method incorporates the impact of science as well as general-purpose technologies, from the Internet to smartphones, where the spillovers are difficult to catalogue and trace. More generally, by looking at net gains in value added, it encompasses imitative spillovers, business stealing spillovers, and other positive and negative impacts of the advance of new ideas.

[8] As vaccines entered use in December 2020, COVID cases in the United States were rising past 200,000 per day and deaths were rising past 3,000 per day. Using "value of a statistical life" measures for the United States of approximately $7-13 million in current dollars (Bosworth et al. 2017), the loss of life in one day (and in just the U.S.) would be valued at or above the entire cost of Operation Warp Speed. Meanwhile, the United States was down 10 million jobs in December 2020 compared to February 2020, and GDP was at least 4% below trend, which equates to several billion dollars lost per day. And this daily GDP loss comes on top of several trillion dollars of government expenditure to stabilize the economy. Indeed, the expenditure on Operation Warp Speed was also tiny (less than 1%) compared to the $3 trillion the U.S. government has spent in pandemic relief through March 2021 (Gross and Sampat 2021).

Operation Warp Speed did was to bring the end of the pandemic one day forward in time, then it easily paid for itself (Azoulay and Jones 2020).

The enormous social return to R&D investments raises a simple question: Why don't we spend more? A striking feature of Operation Warp Speed, at less than 1% of U.S. government expenditure on the pandemic, or of overall U.S R&D expenditure, at 2.8% of GDP, is that we devote a very small share of our resources to these endeavors. Society has a machine that pays back far more than we put into it, yet we put few dollars into the machine. We will return to these issues when discussing policy opportunities in Section 4.

3.b. The public use and funding of science

Even after acknowledging the high returns to R&D as a whole, one may still be doubtful about the role of science investments in this system. These doubts are especially relevant from a policy perspective because the government is a lead funder of scientific research. On the one hand, the logic of public goods and conceptual case for public investment is especially powerful for science, where the immediate marketplace value of new understandings of nature, on their own, may be very low, and therefore are especially unlikely to be provided by the private sector. Yet, as discussed in Section 2, a skeptic may wonder whether scientific research in practice tends to be useful. Perhaps most of scientific research provides no spillovers to support valuable applications. Perhaps the government makes bad investment choices. Perhaps scientists themselves are isolated from practical problems, operating in communities that tend to serve their peculiar and remote curiosities. These issues would all undermine the public case for investing in science specifically, even where the average returns to R&D on the whole are high.

One answer is the study by Azoulay et al. (2019), discussed above, which finds high marketplace returns caused by additional research funding at the NIH. At the same time, that study has a narrow context, focusing on biomedicine and the NIH channel. To generalize, we consider here several "big data" analyses that study linkages between the entire corpus of scientific research, across all fields, and public use in multiple dimensions.

In a recent study, Ahmadpoor and Jones (2017) studied how U.S. patents build on prior scientific research, studying all U.S. patents since 1975 and tens of millions of scientific articles. The analysis investigates the connections between ideas, focusing on ideas that a given patent denotes as relevant prior art. This prior art can be prior patents but may also be scientific research articles.[9] Similarly, scientific research articles build on prior scientific articles. Using the references between documents, one can then trace knowledge flows within and between the domains of science and patenting, and study these flows across the entire landscape of research. Several facts and insights emerge. First, there is "majority connectivity" between the patenting and scientific domains. Conditional on a research article being cited at least once by other scientists, a large majority of scientific articles (79.7%) are part of a stream of knowledge that flows through to a specific future patent.[10] Second, the patents that draw directly on science are the most valuable patents.[11] In particular, these patents are the ones that are most heavily built upon by future inventions. Using similar big data, Watzinger and Schnitzer (2021) show that patents that directly draw on science have an average market value of $17.9 million, which is double the average market value of patents that are disconnected from science (see Figure 1). Finally, the data reveal the institutional sources of advances: In practice, universities and government laboratories produce the vast majority of the scientific articles that patents cite, and private sector businesses produce the vast majority of the patents that cite these articles. Overall, the flow of knowledge from publicly supported science into marketplace invention appears both highly valuable and remarkably widespread.

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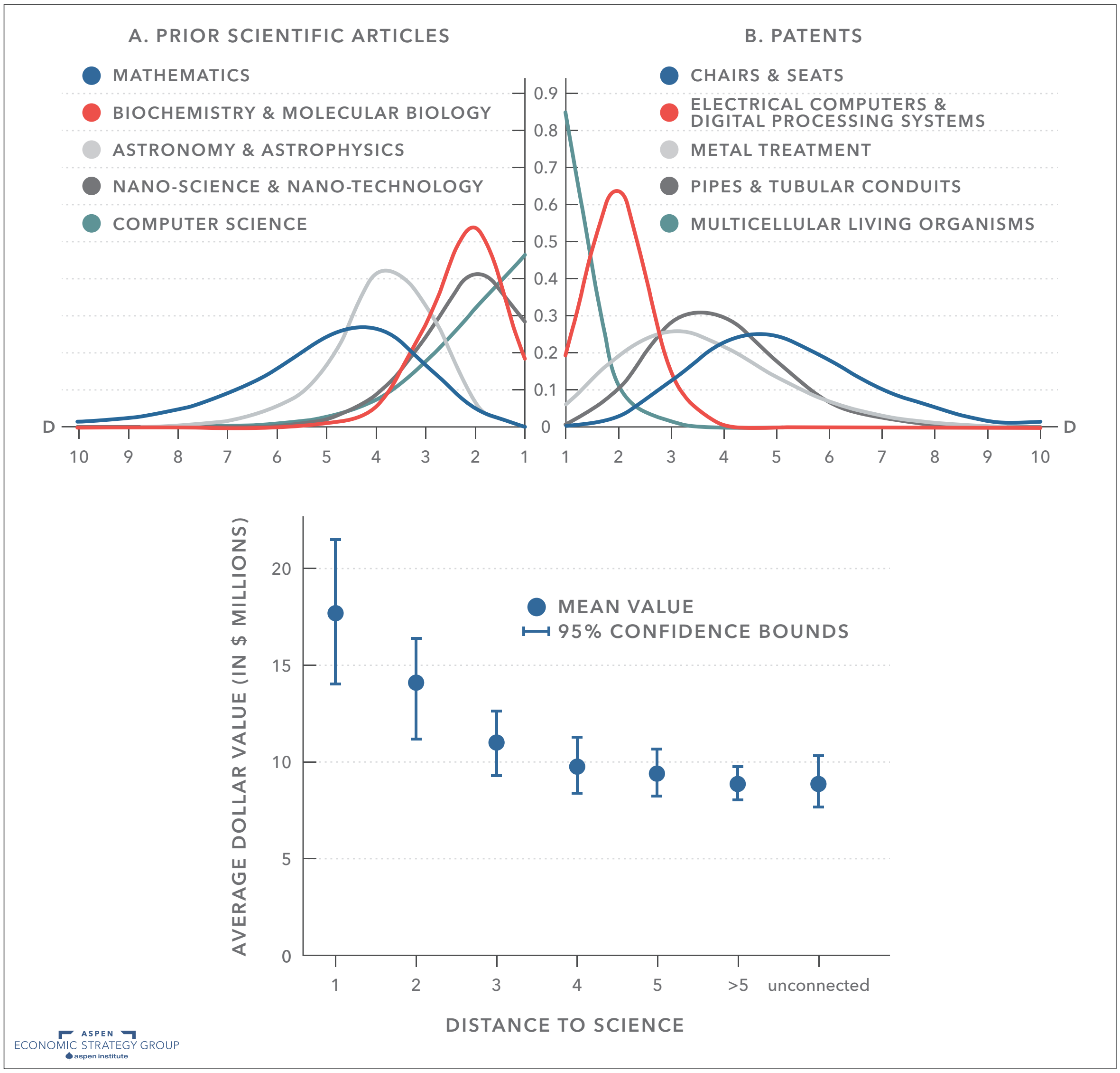
[9] Studying prior art in patent documents has long been used in smaller samples to trace how one new idea builds on another within patenting and between science and patenting (*e.g.,* Carpenter and Narin 1983; Jaffe et al. 1993).

[10] Patents directly cite science in research fields with applied orientations (*e.g.,* computer science, nanotechnology, and virology) but most of the connectivity is indirect, with these directly cited science advances building on other scientific advances, tracing back to increasingly basic science fields like mathematics and physics.

[11] The patenting technology areas that are closest to science include areas such as biomedicine, artificial intelligence, and novel chemical compounds. Conversely, the patenting technology areas most distant from science (and with low market value) include inventions in things like cardboard boxes, ladders, envelopes, and chairs.

Figure 1: The use of scientific research in marketplace invention



Notes: Upper panel: Ahmadpoor and Jones (2017) consider the linkages between patents (right) and prior scientific articles (left), constructing a distant metric, D. The distance D=1 indicates a patent that directly references a scientific article. The distance D=2 is a second-degree citation (a patent that cites a patent that cites a scientific article on the right, or a scientific article cited by a scientific article that is cited by a patent on the left), and so on for higher measures of D. In some technology areas, like electrical computers, patents are close to science, while in others, like chairs and seats, patents are distant from science. Similarly, some fields of science, like nanotechnology, tend to be close to patenting while more basic research fields, like mathematics, tend to be more distant. Lower panel: Watzinger et al. (2021) consider the market value of patents based on how close they are to science. Patents that directly build on scientific articles have twice the market value as those most distant from science.

Further "big data" research has extended the study of science to other public uses. For example, in addition to supporting technological progress, research insights can support public policy and further engage basic human curiosity in the public at large. Specifically, Yin et al. (2021) further link the corpus of tens of millions of research articles not only to follow-on patenting but also to follow-on uses in U.S. federal government documents, across all federal agencies, and follow-on reporting in the general news media. What emerges is a diverse array of specialized use cases for different scientific and social scientific fields. For example, materials science research is used heavily in patents but is rarely referenced in government policy documents or in the news. Economics research, by contrast, is rarely referenced in patents but is regularly referenced in government and in the news. Government uses are very diverse and agency dependent,[12] while the news proves especially interested in human-centric subjects, such as psychology and medicine. Finally, Yin et al. further integrate funding information from major public sources.

This study allows insight on whether public funding, across hundreds of different research fields, is or is not allocated in line with public use of scientific research. What is especially striking is that a field's intensity of use in a given public domain—whether patents, policy, or news—strongly predicts public funding of that field. Pulling all three types of public use together, one can predict the public funding of different scientific fields with remarkable accuracy (see Figure 2).

The picture that emerges from these studies is not one of science and scientists being isolated from the public interest. Rather, science and social science have rich interfaces with public use, whether for marketplace invention, government policy, or general human interest. The science system appears metaphorically like a series of public parks. Many fields are like neighborhood parks—embedded in particular and often specialized communities of use. A few fields—like biomedicine—are more like a large national park, drawing in wide communities of public users and receiving proportionally more funding. Overall, these studies reject views that science is isolated from public use or funded in ways that don't track public interest. The widespread public use of science—and the value science brings—appear striking in the data.

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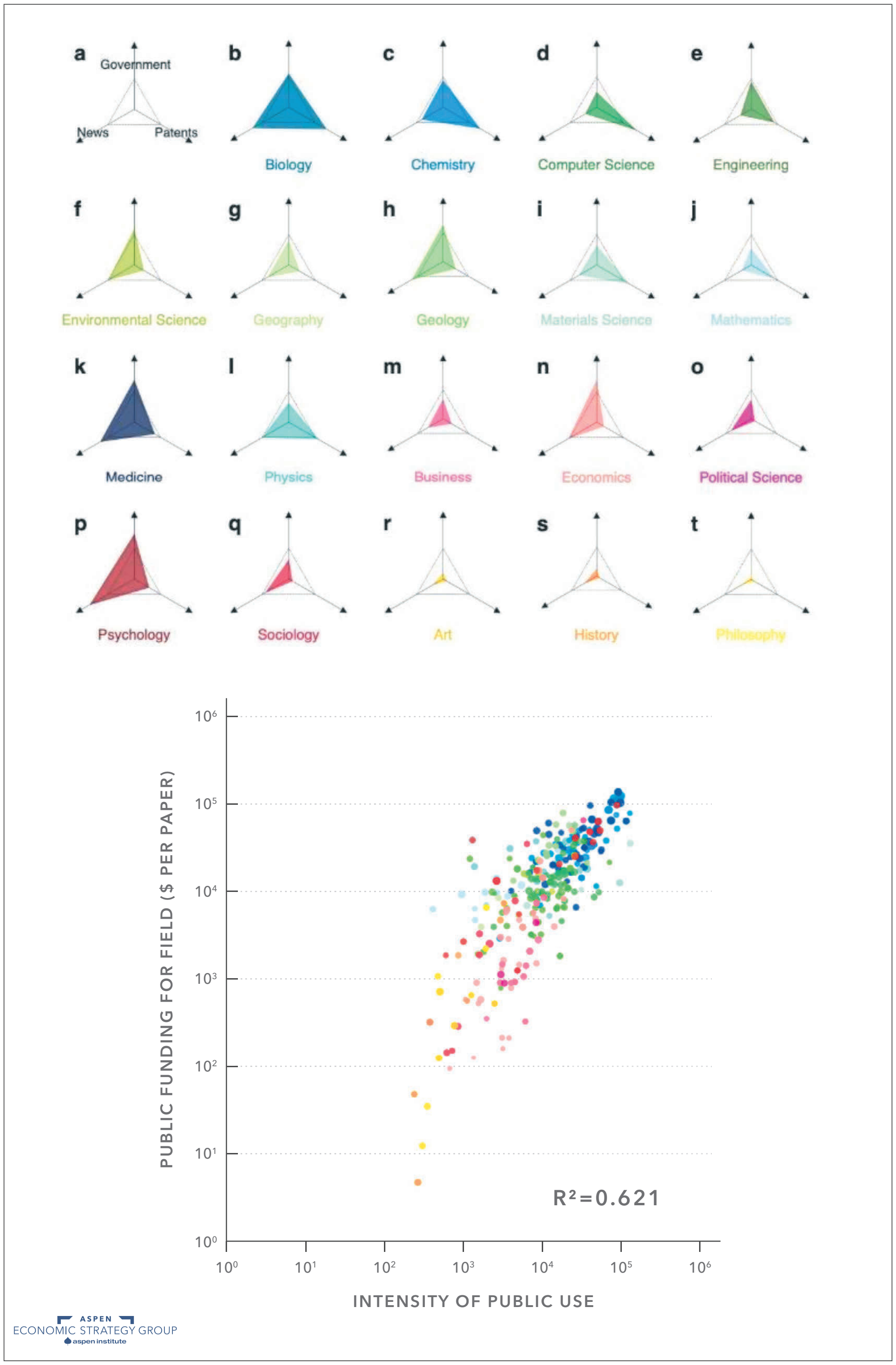
[12] For example, agencies like the Departments of Agriculture, Energy, and Transportation especially consume research in specific hard science and engineering areas related to their missions. The Department of Treasury especially consumes economics and business research, the Department of State draws heavily on political science research, and the Department of Defense is an unusual consumer of history.

Figure 2: The public use and public funding of scientific research



Notes: Upper Panel: When considering references to scientific articles from three public domains– patenting, government documents, and the news media–we see that different scientific fields are drawn upon in distinct and typically specialized ways. For example, computer science research is drawn upon directly and heavily in patenting, but less so in government policy documents or the news media. Psychology research, by contrast, is drawn upon especially by government agencies and in the news media, but much less so in patents.

Lower panel: Dividing the 19 top-level research fields into their 294 constituent subfields, we see that the intensity of public use is highly predictive of the public funding of the field. Source: Yin et al. (2021).

3.c. The people who drive breakthroughs

At the root of the science and innovation system are innovative people—the individuals who drive the advance of ideas. Understanding these "people inputs" is central to understanding the sources of advances and, consequently, to investing successfully in science and innovation. Who are these innovative people, and where do they come from?

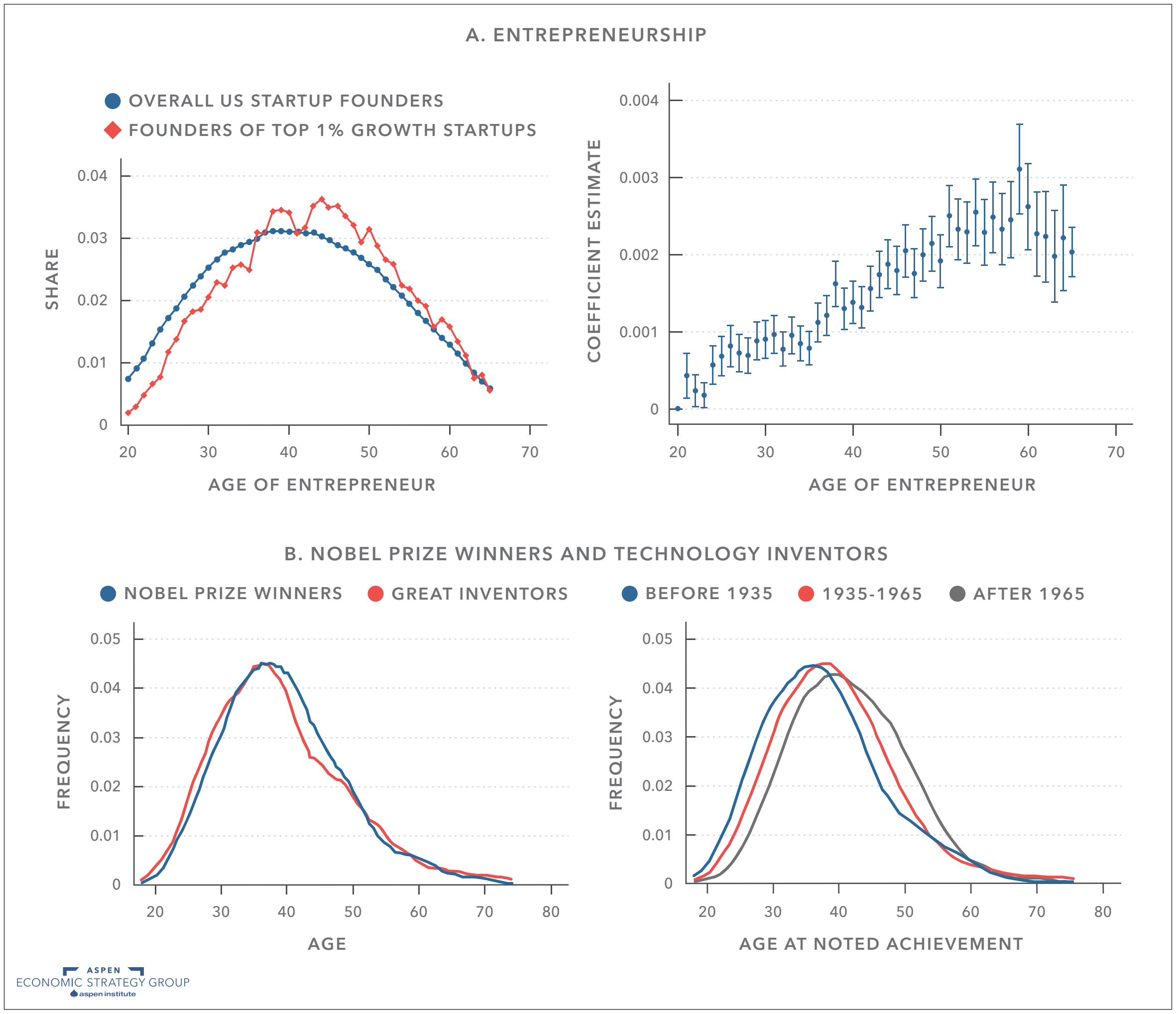
Public perceptions frequently suggest that very young people, often without substantial training, produce the big ideas. This view appears both in science and in marketplace innovation, and it is typically grounded in various viewpoints where younger people have greater levels of creativity, energy, and/or raw intelligence (Jones et al. 2014). The technologist and investor Paul Graham has said "the cutoff in investors' heads is 32 … after 32 they start to be skeptical" when discussing the right age for entrepreneurs, a view widely reflected in both the news media and venture capital behavior (Azoulay et al. 2019). And, in the sciences, people like Albert Einstein, Werner Heisenberg, and Paul Dirac made Nobel Prize winning contributions by the age of 25, suggesting the power of youth. Paul Dirac once opined, in a short poem, *"Age is of course a fever chill / that every physicist must fear / he's better dead than living still / when once he's past his 30th year"* (Jones 2010). These views have strong implications for the "people" part of the science and innovation system, including who should be hired and funded, and whether and how we can scale the relevant workforce.

Recent large-scale data studies have provided increasingly decisive insights on the demographic dimensions of scientists and innovators. First, consider new venture creation. Azoulay et al. (2019) used U.S. administrative data, including demographic information and tax records, to study every new business and every founder in the U.S. economy over the 2007–2014 period. They studied founder characteristics as well as the technology orientation of the business and its growth performance over ensuing years. Because this study considers millions of new businesses, it can focus not only on average outcomes but also on the very "upper tail" outcomes, including the 1 in 1,000 new businesses that saw the greatest sales or employment growth. The findings are striking: Rather than new venture success being the domain of founders in their 20s, or even their 30s, the upper tail successes came from individuals who start businesses at an average age of 45. Moreover, studying the employment histories of each founder, closer and longer work experience in the exact industry in which the new venture operates is extremely predictive of higher success rates. In other words, in contrast to the common ideas that (1) young people and (2) industry outsiders produce the exceptional successes, the reverse is true. Ultimately, age and relevant experience appear as signatures of success (see Figure 3A).

Turning to scientists and inventors, the major breakthroughs also tend to come in middle age. Studying all Nobel Prize winners and famous inventors over the 20th century, Jones (2010) finds not only that their signature breakthroughs tend to come in middle age, but also that they are coming at older ages with time (see Figure 3B). Today, one is more likely to produce a Nobel Prize–winning insight beyond age 55 than before age 30. Overall, in science, invention, and entrepreneurship, breakthroughs tend to come not from the young but from more seasoned individuals, deep in their domains.

In studying breakthroughs, one can also look more precisely at the role of expert knowledge. Here there is a key challenge that confronts science and innovation and is reshaping the "people" part of the science and innovation system. In particular, the very progress of science and technology means that there is more collective knowledge in each generation. This is one reason scientific advance is shifting away from breakthroughs by young people – who, in deepening areas, have more to learn before producing the next big steps (Jones 2010). But more generally this accumulation of knowledge across generations means that experts are increasingly specialized (Jones 2009). As Albert Einstein once said, "[K]nowledge has become vastly more profound in every department of science. But the assimilative power of the human intellect is and remains strictly limited. Hence it was inevitable that the activity of the individual investigator should be confined to a smaller and smaller section…" (Einstein 1949). Following Einstein's dictum, studies of the entire landscape of scientific research and patenting show exactly this: patterns of increasingly narrow expertise with time (Jones 2009; Jones 2011; Schweitzer and Brendel 2019; Hill et al. 2021).

Figure 3: Sources of scientific and innovative breakthroughs



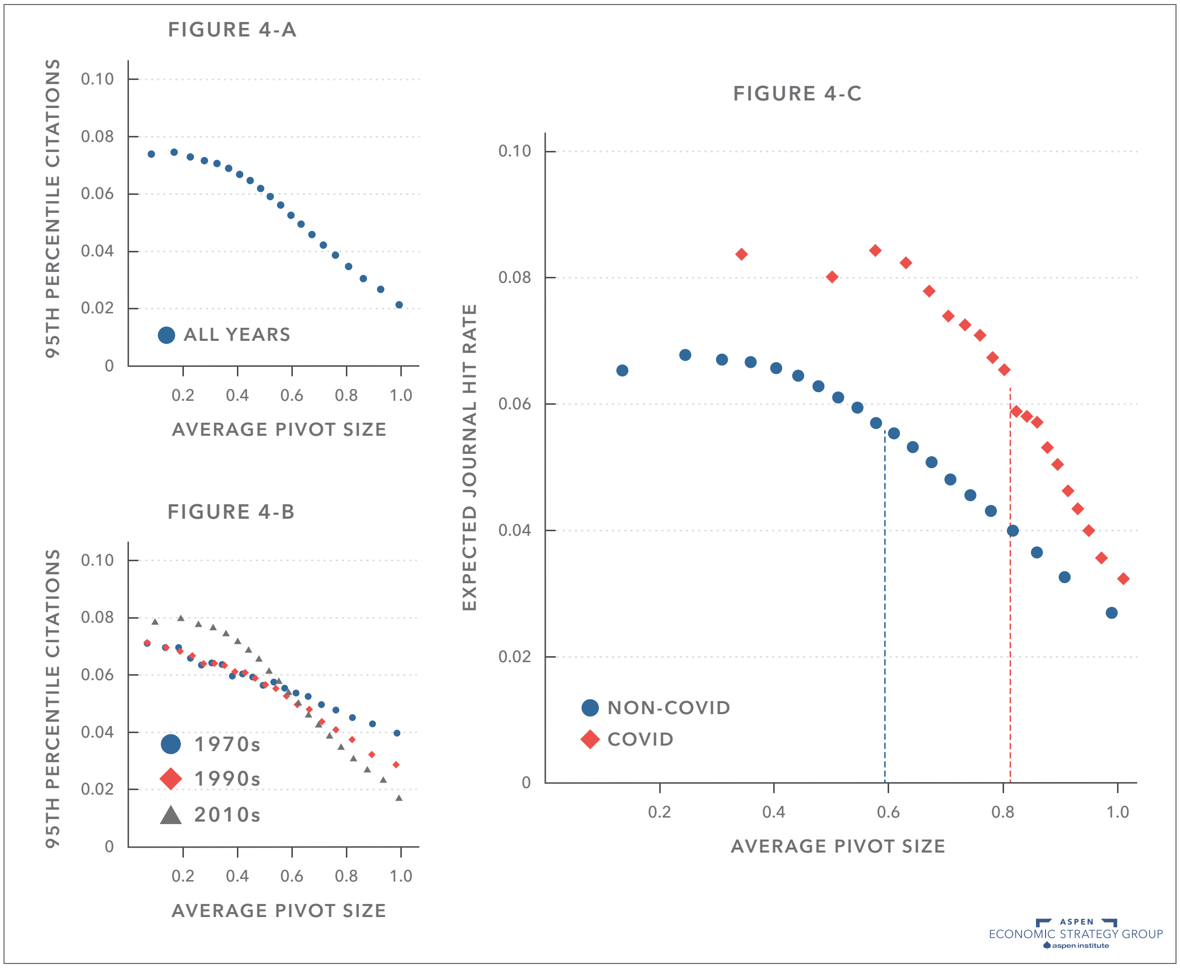
Notes: Contrary to common perceptions, science and innovation are not driven by young people with little domain expertise. **(3A)** The highest-growth, new ventures in the United States come from middle-aged founders (left). In fact, conditional on starting a firm, the probability that a founder has an upper tail success is increasing steadily and substantially with the founder's age (right). The data are all new ventures and founders in the United States from 2007–2014. Source: Azoulay et al. (2020). **(3B)** Similarly, the most notable science and technology breakthroughs come from individuals in middle age (left)–and from increasing ages with time (right). The data here are all Nobel Prize-winning contributions and the major inventions of the 20th century. Source: Jones (2010).

This narrowing of individual expertise has key implications for how we find breakthroughs. Namely, across all research areas, scientists and inventors increasingly work in teams, which act to aggregate expert knowledge and skills and allow researchers to attack problems more successfully (Mesmer-Magnus and DeChurch 2009; Lee et al. 2015). Critically, the highest impact science and the most valuable patents—whether from universities or private sector firms—increasingly come from larger teams (Wuchty et al. 2007). Today, the "people" part of scientific and technological progress has become not only a story of expertise, but a story of increasing specialization and collective expertise.

The narrowing of expertise also has implications for another key role of science and innovation: managing major crises. For example, Hill et al. (2021) study the response to COVID-19 across the entire landscape of scientific research. They show that an enormous range of scientists pivoted their research streams to engage the pandemic. In fact, nearly 6.3% of publishing scientists wrote a COVID-19 research article in 2020. However, the highest-impact COVID-19 research came, by far, from people who pivoted the least: Those who were already working on the very particular specialized topics that were closely positioned to engage COVID-19. This includes the University of Texas and NIH researchers who identified the COVID-19 spike protein as a key therapeutic target (Wrapp et al. 2020). Similarly, vaccines came not from outsiders but from specific scientists in private sector firms (such as Moderna and Pfizer-BioNTech) who were already specialized in the relevant mRNA platforms and could rapidly create solutions that targeted this spike protein. Stepping back from the pandemic and looking across all scientific research over the last five decades, researchers have become increasingly impactful when staying in their narrow domains and increasingly unable to make high-impact contributions outside their narrow domains (Hill et al. 2021). See Figure 4.

Ultimately, the picture of scientists, inventors, and entrepreneurs that emerges in these “big data” studies is one that emphasizes the importance of expertise—and the increasing importance of expertise. While science and innovation investments are probabilistic bets, and young and relatively inexperienced individuals can and do make large contributions, the weight of contributions increasingly come from older individuals with deep domain knowledge, and from specialists working in expert teams. A key implication is that critical resources of science and innovation depend on substantial human capital investments, which cannot be made overnight, but rather require effort and time to develop. The policy implications will be further considered in Section 4.

Figure 4: Expertise, specialization, and the pivot penalty



Notes: Scientists are increasingly specialized, and science increasingly relies on specialized domain experts to produce high-impact work. These figures examine this phenomenon by asking what happens when researchers work within or outside their domain expertise. In each panel, the pivot size measures how far a scientist is moving from their prior domain knowledge when writing a new article. The vertical axes are the probability of a high impact research article. Upper left: High impact work comes when a scientist stays close to their prior research expertise. Lower left: The penalty for moving away from one's specialized area is getting worse with time, indicative of an increasing advantage of domain expertise. Right: In 2020, enormous numbers of researchers pivoted to engage COVID-19, and this research experienced an impact premium given the critical demands of the pandemic. But even as scientists pivoted to help, the pivot penalty prevailed, with the highest impact work coming from individuals with relevant pre-existing domain expertise and who pivoted the least. The data are tens of millions of scientific articles across all of science, historically and today, and all COVID-19 research articles. Similar findings appear in patenting. Source: Hill et al. (2021).

4. Policy opportunities

We have now considered evidence, including recent studies and systematic evidence, to sharpen understanding of the science and innovation system in practice. In light of this evidence, we now ask how we can reshape public policy, emphasizing first-order policy dimensions to better engage the opportunities in science and innovation investment and meet the national interest.

4.a. The scale of investment

The United States appears to greatly under-invest in R&D. Studies, including the latest studies, find that the social benefits from these investments are extremely high. A central number from Jones and Summers (2020), which looks at the returns to science and innovation investment across the U.S. economy, suggests *conservatively* that $1 invested brings society $5 back on average. While one can debate specific numbers, the point that R&D investments bring extraordinary social returns appears highly robust.[13]

The question then for society is why we don't put more investment dollars into the science and innovation machine. R&D expenditure in the United States has averaged 2.8% of GDP over the past decade, representing a small share of economic activity. Even a 50% increase in total R&D expenditure, to 4.2% of GDP, would still call on a modest share of resources. Since some other countries already surpass such high R&D investment rates,[14] it seems practicable for a nation to invest substantially more in R&D. To understand why economies fall short, and leave such high-return investment opportunities untapped, we return to the public goods nature of innovation and the role public policy in putting additional dollars into the machine, whether to invest in basic research or to help encourage the private sector. As things currently stand, we appear to have a massive investment failure. Society has this incredible machine to raise standards of living, health, and worker productivity, yet we collectively fail to engage the machine to an extent commensurate with the benefit it appears to deliver.

That the United States doesn't invest more is even more striking in light of recent and evolving challenges. The United States has faced a slowdown in productivity growth and rising concern about the international competitiveness of the U.S. workforce over many years (*e.g.,* Gordon 2012; Autor et al. 2013), where real wages for the median household have struggled to rise and failed to keep pace with the gains in prior generations (*e.g.,* Council of Economic Advisers 2011; Autor et al. 2006). Yet, even as productivity has lagged, U.S. R&D intensity has slipped compared to other countries. In the mid-1990s, the United States was in the top five of countries globally in both total R&D expenditure as a share of GDP and public R&D expenditure as a share of GDP (Hourihan 2020). Today, the United States ranks 10th and 14th in these metrics, and U.S. public expenditure on R&D as a share of GDP is now at the lowest

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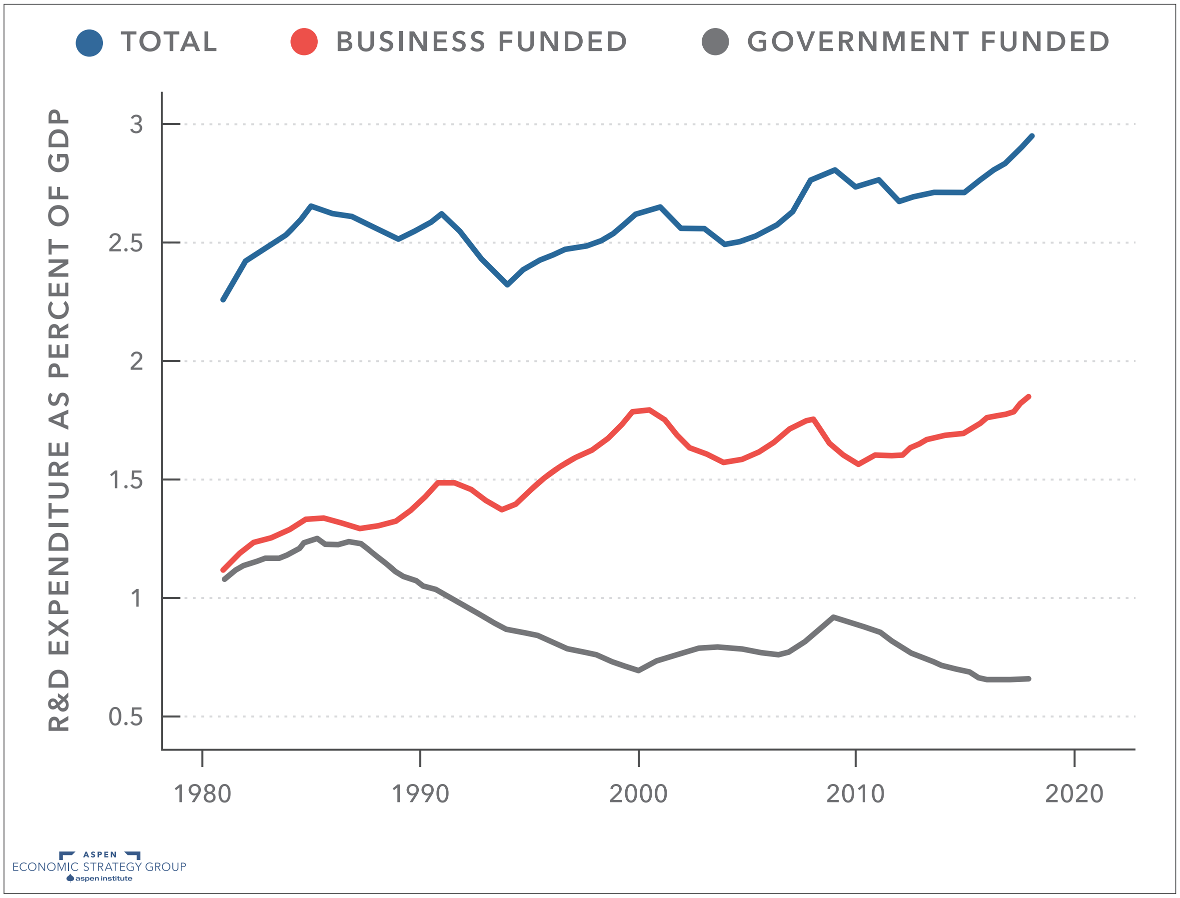
[13] A related question concerns the optimal level of R&D investment. With more investment, we eventually hit "diminishing returns," where the value of additional R&D investment will decline. But we appear to be very far from that point now. For example, studies like Azoulay et al. (2019) and Bloom et al. (2013) show directly that additional investment in R&D produces enormous social returns on the margin. Jones and Williams (1998) suggest that optimal R&D investment levels in the United States should be, conservatively, two to four times higher than actual investment. For additional discussion, see Jones and Summers (2020).

[14] For example, South Korea (4.6%) and Israel (4.9%) greatly exceed even an ambitious target like 4%, and many leading economies now substantially exceed U.S. R&D intensity, including Japan (3.2%) and Germany (3.2%).

level in nearly 70 years. See Figure 5 for U.S. trends. By contrast, China has massively increased its science and innovation investments in pursuit of leading the world economically and strengthening its hand in global affairs. China's R&D expenditure has grown 16% annually since the year 2000, compared to 3% annually in the United States. If China implements its current five-year plan, it will soon exceed the United States in total R&D expenditure.

Figure 5: U.S. R&D spending over time



Notes: Trends in U.S. R&D expenditure as a share of total U.S. GDP. Government R&D investment has been in a long decline. Federally funded R&D support as a share of GDP is now approximately half its level from the 1980s and more generally is at its lowest level in nearly 70 years. Source: OECD Main Science and Technology Indicators (2021).

Partly in response to these patterns, the U.S. Senate passed bipartisan legislation in June 2021 that authorizes expansions of public R&D investment. Within the provisions of the U.S. Innovation and Competition Act, there are authorizations to increase public R&D expenditure by approximately $90 billion, spent over five years, with the additional investment flowing primarily through the National Science Foundation, Department of Energy, and Defense Advanced Research Projects Agency (DARPA). This legislation is moving to seize the social returns to greater R&D

investment. It promises to increase the productivity and competitiveness of U.S. businesses and the U.S. workforce, and it is being promoted by policymakers with a competitiveness orientation.

An observation about U.S. science and innovation policy is that policymakers appear to go big (or, at least, go bigger) when perceiving specific threats. This was the case in World War II. It was the case with Sputnik and the Apollo program. It was the case with COVID-19 and Operation Warp Speed. And it is the case currently with China and developing legislation like the U.S. Innovation and Competition Act. The past efforts have tended to produce notable and world-leading advances—from radar and jet engines, to walking on the moon, to effective vaccines (Gross and Sampat 2021). What is an open question about our political economy is why we don't go even bigger, and do it all the time. For example, the U.S. Innovation and Competition Act is moving substantively in the right direction but still envisions only a modest increase in R&D intensity, raising the R&D share of GDP by about 0.1 percentage points. This is modest compared to what is already achieved in some other countries, and it is modest compared to the rising expenditure in China. Most importantly, it is modest compared to the gains that are on offer.

Looking purely at the social returns, the standard findings suggest that doubling the total investment in R&D would easily pay for itself (Jones and Williams 1998; Bloom et al. 2013; Jones and Summers 2020). That is, the additional expansion in standards of living in terms of GDP per person would be much larger in present value than the additional investment cost. How much potential is the United States leaving on the table? Using the general approach in Jones and Summers (2020), a sustained doubling of all forms of R&D expenditure in the U.S. economy could raise U.S. productivity and real per-capita income growth rates by an additional 0.5 percentage points per year over a long time horizon. This would lead to enormous increases in standards of living over time. It would greatly advance the competitiveness of U.S. businesses and workers and the overall position of the U.S. economy in the world. And this economic orientation leaves out the health gains of longer and healthier lives, which are among the most valuable deliverables from the science and innovation system (Cutler et al. 2006; Murphy and Topel 2007; Jones and Summers 2020).

4.b. The people pipeline

Successfully scaling up the science and innovation system, and achieving its many benefits, will rely on more than just increasing R&D expenditure. It also requires scaling the science and innovation workforce. These are the people who actually produce the breakthroughs, and systematic evidence about the people part of innovation (see Section 3.c) emphasizes that breakthroughs come from people with particular characteristics. While big ideas can come from many corners, they tend not to come from young people with little domain knowledge but rather from domain experts in middle age and beyond. The people who hit the "home runs" are typically individuals steeped in an industry when creating new ventures and typically specialized experts working in teams in both marketplace invention and in scientific research.

An immediate policy implication is that the people part of innovation cannot easily be extended overnight. Rather, expanding the science and innovation workforce requires investment to cultivate individuals with relevant training and talent. A number of recent studies, all utilizing high-scale data, further inform the sources and constraints in expanding this workforce. Here we consider the medium and longer-run opportunity through the U.S. educational system as well as the relatively rapid scaling opportunities through immigration policy.

4.b.1. Domestic investment in STEM workers

Recent studies have used comprehensive data to study the childhood backgrounds of inventors, including recent U.S. inventors (Bell et al. 2019), historic U.S. inventors (Akcigit et al. 2017), and inventors outside the United States (*e.g.,* Aghion et al. 2017). A striking finding is that inventors come from quite narrow parts of the overall population. Specifically, they tend to be male, they tend to be born in high-income households, and they tend to have been exposed to inventive careers as children. These studies and others further emphasize that there is enormous potential to expand entry into these career pathways—that is, the talent demonstrated at young ages is far wider than the set of people who enter these careers. In identifying career impediments, one also sees concrete opportunities to expand entry.

Consider for example mathematical ability demonstrated at young ages. Bell et al. (2019) study the 3rd grade test scores throughout New York City and observe the career pathways that eventually develop for these children. While very high math scores in 3rd grade are highly predictive of entry to invention later, this effect is much weaker among kids with equally high math scores if they come from lower-income households. Similarly, girls with extremely high math scores in 3rd grade are much less likely to enter invention later. At the same time, exposure to inventive career opportunities appears to be a powerful mechanism to encourage future entry. Studying the entire United States, children that grow up in neighborhoods with high invention rates are more likely to become inventors and will tend to patent in exactly the same technology area that they have been exposed to as children. Further, children who move to more inventive regions during childhood become far more likely to enter inventive careers. And girls who move to regions that are especially populated with female inventors become far more likely to become inventors themselves.

Altogether, these findings suggest two key things. First, there appear to be many "lost Einsteins" in the U.S. science and innovation landscape, where very talented kids miss out on these career opportunities. Talent does not appear to be a constraint on the U.S. capacity to scale science and innovation efforts. Second, among other potential educational interventions, exposure to innovation career pathways offers potentially low-cost, high-return policy approaches. Extending mentoring and social networks between the nation's existing inventive workforce and children from lower-income backgrounds, girls, other underrepresented groups, and those in neighborhoods with less inventive activity appear as large opportunities to expand pathways into the science and innovation system.

Stepping back, opening pathways into the STEM workforce would not only help propel standards of living, health improvements, and the U.S. position in the world, but it would also directly expand individual opportunity and reduce inequality. In particular, rising inequality in the United States over many decades is a story of increasing labor market and wage gains for highly educated workers, and a corresponding weakening job market for those with less education (*e.g.,* Goldin and Katz 2010). Sending more children into STEM careers will serve to reduce these wage gaps.[15] Cultivating untapped STEM talent among under-represented groups and in currently less-inventive areas, whether in cities or in rural areas, may have especially impactful job and wage effects. Thus, expanding the STEM workforce along these lines would appear as a win across many dimensions of society, not only accelerating standards of living gains and competitiveness but also help address inequality, including regional inequality, and structural labor market issues. From this perspective, a big push on developing the STEM workforce, could be a unifying, bipartisan policy step.

4.b.2. Immigration opportunities

The opportunities discussed above provide major pathways to expanding the people part of the innovation system. However, developing the talent pool for science and innovation through the education system, and especially early life-cycle efforts, will bear fruit relatively slowly. More rapid pathways are also available. In particular, a country can import talent (*i.e.,* through immigration). Recent, systematic studies of entrepreneurship and invention in the United States help inform this channel.

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[15] This is a point about supply and demand. Namely, labor force adjustment that makes highly trained STEM workers more abundant (and less-educated workers less abundant) will help those who remain less-educated: they will see more job opportunities per person and relative wage gains.

In a systematic study of inventors in the United States, Bernstein et al. (2019) examine the role of immigrants in U.S. invention. The central finding is that immigrants are especially productive in inventive activity. Not only do immigrants patent more often than U.S.-born individuals, but their patents are both more impactful for future invention and have greater market value. Overall, immigrants produce twice as many patents as one would expect from their population share. This is consistent more broadly with the STEM orientation of the immigrant workforce. While immigrants make up about 14% of the U.S. workforce, they account for 29% of the college-educated science and engineering workforce and 52% of science and engineering doctorates (Kerr and Kerr 2020). Overall, immigrants have accounted for about 30% of U.S. inventive activity since 1976 (Bernstein et al. 2019).

A similar picture emerges when examining entrepreneurship. Azoulay et al. (2021) study every new venture in the United States founded from 2007 through 2014 and examine whether the founders were born in the United States or abroad. They find that immigrants are 80% more likely to start a company than U.S.-born individuals. Moreover, immigrant founders are more likely to start companies of every size, including the highest-growth and most successful new businesses (see Figure 6).[16] Indeed, looking at Fortune 500 firms today and tracing them back to their founding roots, one similarly finds a disproportionate role of immigrant founders—from Alexander Graham Bell to Sergey Brin to Elon Musk. A remarkable finding here is that immigrant-founded firms employ more people in total than there are immigrants in the U.S. workforce.

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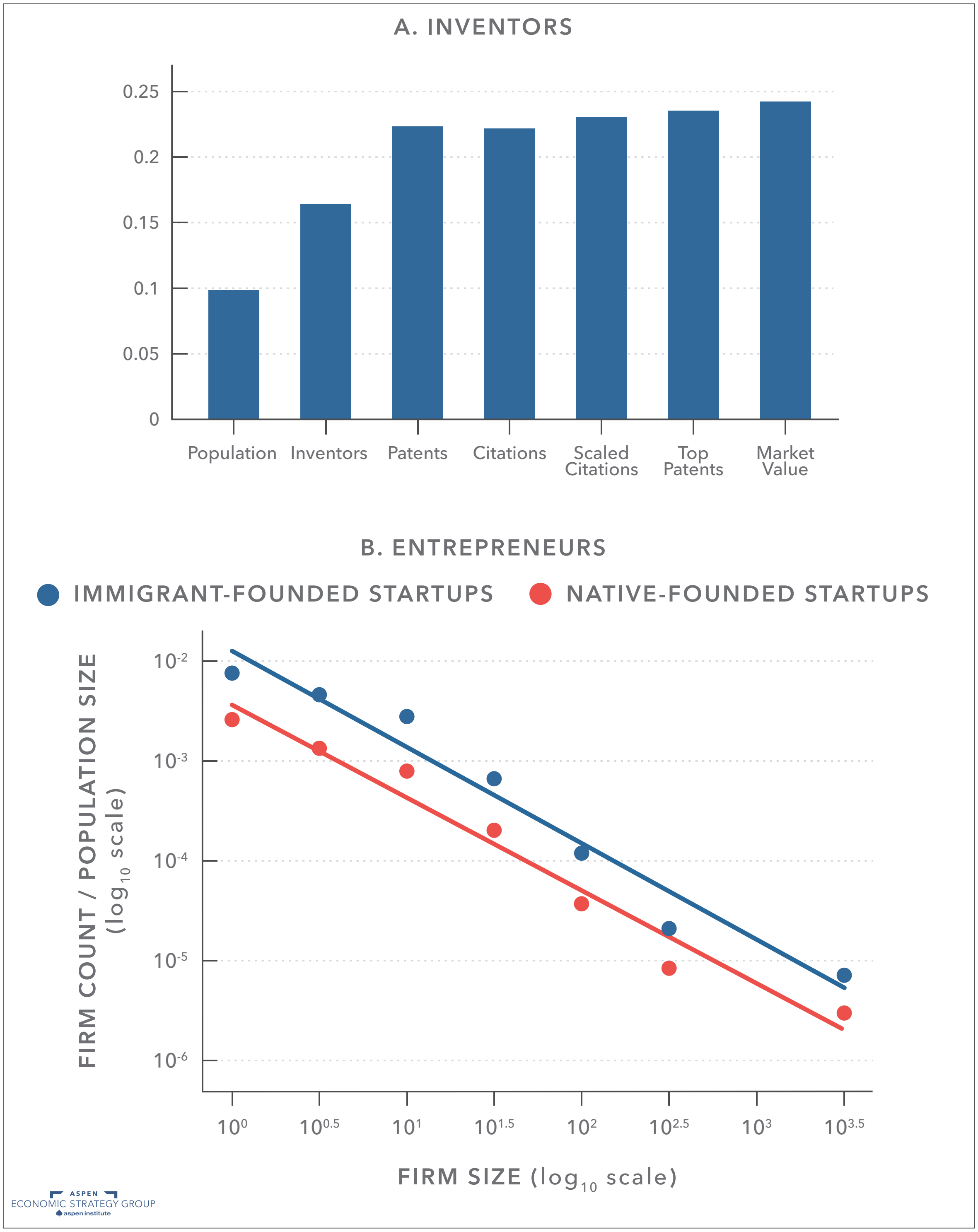
[16] Moreover, looking at the technology of these firms, and consistent with the patenting findings discussed above, immigrant-founded firms are also more likely to patent at all sizes.

Figure 6: Immigrants in the U.S. innovation system



A. INVENTORS

B. ENTREPRENEURS

Notes: Immigrants play especially productive roles in U.S. invention and entrepreneurship. **(6A)** While immigrants have represented 10% of the population since 1975, they have produced more than 20% of the patents, and an even greater share of the highest value patents. Source: Bernstein et al. (2019). **(6B)** Immigrants start new businesses at a rate 80% higher than U.S.-born individuals do. Moreover, immigrants start more firms of all sizes, including the most successful businesses that have the largest sales or employment. Source: Azoulay et al. (2020).

These recent, systematic studies show that immigrants are especially inventive and entrepreneurial. Moreover, the immigration channel may be a relatively rapid way to scale the people pipeline into the U.S. science and innovation system. Given that U.S. immigration policy currently constrains the entry of high-skill workers, there appears to be substantial further opportunity to rapidly expand the science and innovation workforce through immigration policy channels. Kerr and Kerr (2020) examine a range of policy options, including relatively small policy changes, that could make a difference to the innovation system along these lines.

4.c. The portfolio of investment

There are many specific directions of travel when thinking about the problems that we might scale R&D to solve—from Alzheimer's disease to violent crime to quantum computing to space travel. And there are many levers of public policy that can increase investment in science and innovation—from scaling basic research funding to expanding businesses' research and experimentation tax credit. When scaling the national investment in R&D, how should we think about the portfolio of investments? This final section considers these questions.

4.c.1. The importance of independent bets

In searching for as-yet undiscovered solutions, it is essential to remember a key feature of science and innovation investments: the regularity of failure (see Section 2.a). This inherent feature in creative search has important implications for the set of investments that are made as part of a successful R&D policy. First, we must embrace risk. That is, we must not only tolerate failure but embrace it in pursuit of opening new doors to progress. Second, we must engage a wide portfolio of bets. This approach can produce more efficient search, lower collective risk, and increase returns in the science and innovation system.

To illustrate this advantage, consider a search process to find a solution to a particular disease. Let's say that there are a number of pathways to try, but each has a low chance of success—say just 10%. Now let's say that we can make 10 investments in attempts to solve the disease. If all these investments try the same pathway, then the chance of producing a success is still only 10%. But if each investment tries a different pathway, each with an independent 10% chance of success, the collective probability of at least one success rises to 65%. By spreading out the bets, the chance of success is multiples higher, and for the same investment cost.

Public policy can play a key role in pushing for diverse pathways. And the U.S. government has taken this approach explicitly, particularly in crisis situations. For example, Operation Warp Speed explicitly chose to invest in four different vaccine platforms, with two vaccine candidates in each platform. The former director of Operation Warp Speed emphasized this diversification as the first principle of the policy design (Slaoui and Hepburn 2020). Similarly, in World War II, the U.S. Office of Scientific Research and Development (OSRD) was created to coordinate an enormous range of science and innovation investments that would help win the war. These efforts explicitly deployed a portfolio approach, engaging multiple pathways toward a given objective. The development of radar, sonar, high-scale antibiotics, early computing, and the atomic bomb were among the many rapid achievements of the OSRD's efforts (Gross and Sampat 2021).

The key lesson here is that science and innovation investments gain large advantages by spreading out along the frontier of opportunities. This can greatly accelerate progress, and not just in crisis but in ordinary times. But it's not clear that either the private sector or the public research institutions bet widely enough. Rather, we seem to crowd into particular areas. This can be true in the private sector, where businesses may duplicate others' R&D efforts as they compete for a market (Zeira 2011; Bryan and Lemus 2017). And it appears true in scientific research, too. For example, the Human Genome Project unveiled an enormous range of new pathways—*i.e.,* genes that encode proteins, the function of which we do not understand and may be key to advancing human health. Yet Edwards et al. (2011) describe "too many roads not taken," where 75% of protein research continues to focus on the 10% of genes that researchers already knew about prior to the Human Genome Project. In other words, scientists herd, too.[17] Research institutions thus need to focus on seeding and building new communities to further explore the roads not traveled amidst the vast unknown.

Ultimately the constraint on scientific progress is not the set of problems we would like to solve. Nor does it appear to be available pathways of discovery. Rather there is enormous opportunity to scale and diversify these efforts. In many ways, the vision of science and innovation needs to be the opposite of "picking winners." Rather, we need to "pick portfolios," with an emphasis on both increasing the scale of funding and human capital, and the diversity of approaches that are taken. The OSRD and Operation Warp Speed examples provide explicit institutional models, whereby public policy has appeared to play key roles in diversifying bets in effective manners.

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[17] Among the reasons that scientists herd into particular research areas is that they depend on having a relevant community of co-specialists around their work—scientists who collaborate, listen, evaluate, and collectively propel progress in very specific areas (Stoeger et al. 2018). As knowledge deepens, and scientists become more specialized (see Section 3.c), this need for community is likely only to intensify and becomes critical for advance. That is, science is a team sport, and scientist communities may have an effective minimum size. This will inhibit diversification of research pathways, and it links the capacity to diversify pathways of research to the overall scale of the scientific enterprise.

4.c.2. R&D policy levers and uncertainty

The range of mechanisms by which public policy works to expand R&D investment is large and complex. For basic and applied research, an array of federal government agencies solve the market failures by funding projects up-front. Lead investors include the Department of Defense, the NIH, Department of Energy, and the National Science Foundation. Their funding largely goes to a network of national laboratories and to research universities but can also work through private-sector research contracts.[18] Meanwhile, to increase market incentives for invention, the U.S. government supports the intellectual property system, including the U.S. Patent and Trademark Office. Other prominent, market-oriented policies include the R&E tax credit, which lowers innovation costs for private sector businesses, and the Small Business Innovation Research (SBIR) program, which helps fund R&D efforts by small technology businesses and new ventures. On education and workforce dimensions, policies that develop the STEM workforce, from early childhood through graduate school, as well as through immigration, further support the science and innovation system.

Examining this wide range of policy levers, one may ask which approaches are especially effective. And important progress has been made in evaluating specific policy approaches. For example, R&D tax credits for firms, the SBIR program, and NIH research funding appear quite effective at raising innovative investment and with high returns. Recent reviews of specific policy opportunities include Bloom et al. (2019) and Jones and Goolsbee (2021), which provide guides and assessments across wide arrays of policy areas.

At the same time, there remains much about R&D policy that we do not know. This is true especially in a comparative sense across different levers. For example, despite enormous progress in understanding science and innovation, we cannot yet credibly determine whether the investment returns are ultimately higher for basic research (say, in pure mathematics) compared to applied research (say, in nanotechnology materials) or how the social returns to upstream science investments compare to marketplace levers like the R&E tax credit. This puts policymakers in a seemingly uncertain position when assessing how to allocate budgetary resources across the science and innovation system. However, what we do know, and what this chapter has emphasized, is that the social returns to R&D investment overall are extremely high. And this point has strong implications for policy.

Consider again the social returns to R&D. Society has an R&D machine, where we put in $1 and receive at least $5 back. However, extending the picture, this machine

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[18] Federal agencies, and subcomponents of these agencies, use a wide array of funding models. See Azoulay and Li (2020) for an overview and discussion.

turns out to have a complex interface: There are many input slots in this machine, each able to take a dollar—one input slot for the NIH, one for DARPA, one for R&E tax credits, etc. Which slots should we put our dollars in? While there is substantial evidence that many of these input slots produce high returns, lingering uncertainty over which options are best may create pause, debate, and a failure to act. But paralysis would be a huge mistake. Yes, one might get even more dollars back if we knew better how to allocate investments across these slots. But the true failure is not to put more resources into the machine, because with what we already know—based on the allocation we already do—we are getting an enormous return.

Separately, policy uncertainties can be resolved with time, and explicit effort, through science itself. Much has been learned about how science and innovation operate, and where breakthroughs come from. Further advancing our understanding will depend on continued research effort, and the scientific toolkit is powerful here, from the expanding access to comprehensive data about scientists, inventors, entrepreneurs, and their funders, to the expanding set of empirical tools, which include experimental, network, and machine learning methods. Continuing research will sharpen our choices and promises to raise the social returns even further.

5. Conclusion

Science and innovation investments are central to the national interest. These investments can create higher standards of living, longer and healthier lives, and an increasingly competitive workforce. They can support national resilience in the face of crises, like the global pandemic, and they can sustain national leadership in the world, including on economic, political, and security dimensions. Given these potential benefits, this chapter has considered whether the United States invests enough in science and innovation, and specifically whether greater public support is warranted. We have asked several related questions: What are the arguments for or against a public role in the science and innovation system? What is the evidence? How are we doing? What policy changes do we need?

A primary case for public action sees new ideas – the fruits of science and innovation -- as "public goods" that the private sector will underprovide. Meanwhile, skeptical perspectives emphasize the regularity of failed R&D efforts, doubt the capacity for successful public investment, and question the role of science and domain experts in driving practical and important advances. After laying out these different perspectives and illuminating them with examples, the chapter turned to systematic evidence, including the very latest evidence. The conclusions from systematic evidence are clear. The social returns to R&D investments are enormous and greatly in excess of the private returns. Public investments in science appear closely aligned with public use, and domain experts are the primary drivers of breakthroughs in both science and marketplace innovation. In short, the U.S. science and innovation system as it stands delivers far more than its resource costs, and we underinvest in science and innovation to an enormous degree. For every $1 we invest, we conservatively receive $5 in benefit. Effectively, the public has at hand an extraordinary machine to benefit human progress and the national interest, yet we fail to use this machine anywhere close to its full capacity.

To meet the national interest, policy can adapt in first-order, high-return ways. This chapter has emphasized three poles of action to reap the rewards: (1) scaling funding resources; (2) scaling the people pipeline into science and innovation careers; and (3) making diverse investments across the landscape of opportunities. These investments promise to raise our standard of living, accelerate progress against disease, increase the competitiveness of the American workforce, solve for national and global crises, and secure the nation's leadership in the world.

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